22 February 2011 Christchurch Earthquake: Are we adequately characterizing extreme/rare events?

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Overview

- Discussion of the 22 Feb 2011 Christchurch Earthquake in the context of characterization of phenomena
  - Seismic source
  - Ground motion
  - Response of local geology/soils
  - Liquefaction and associated damage
  - Response of structures
  - Infrastructure consequences
- How can we improve characterization?

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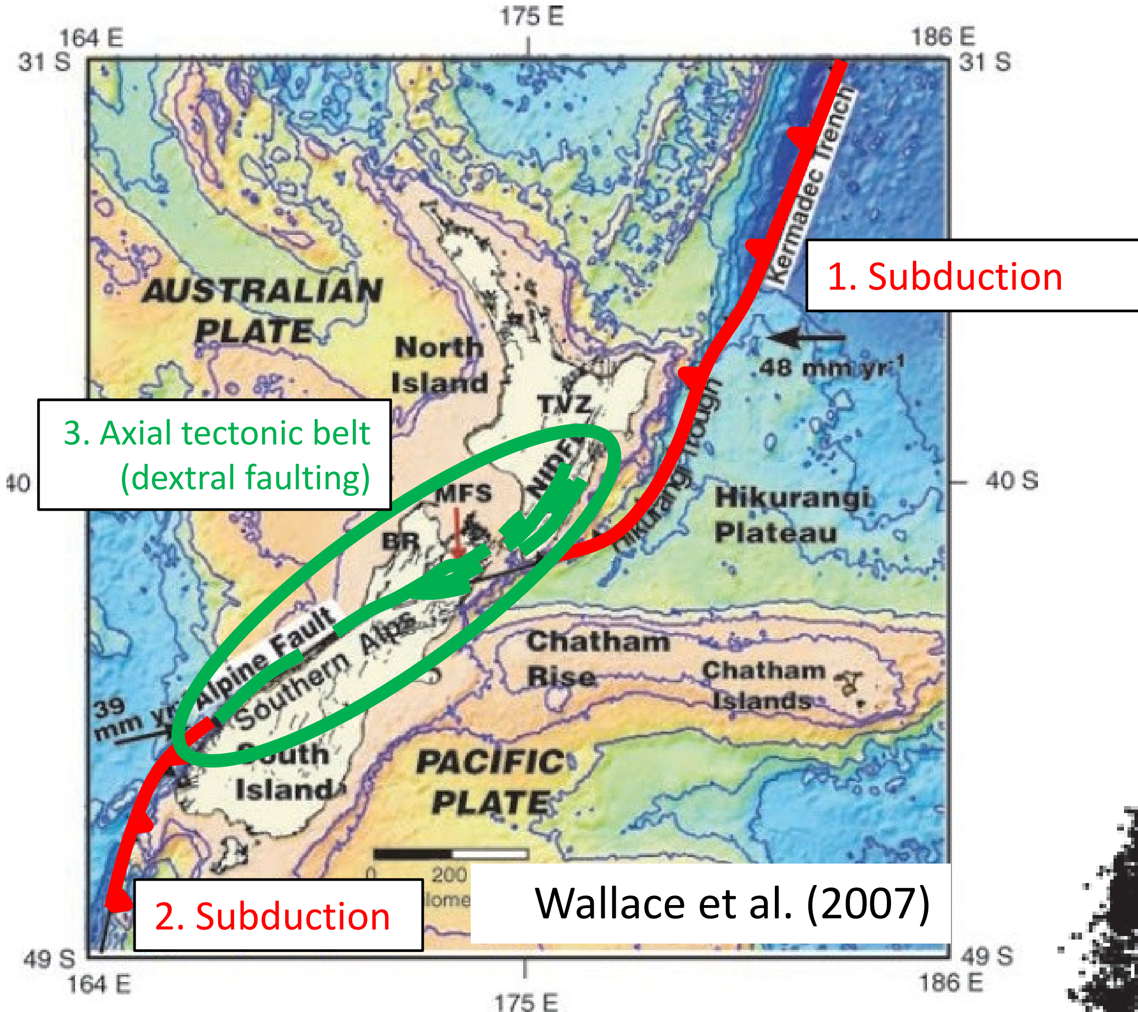
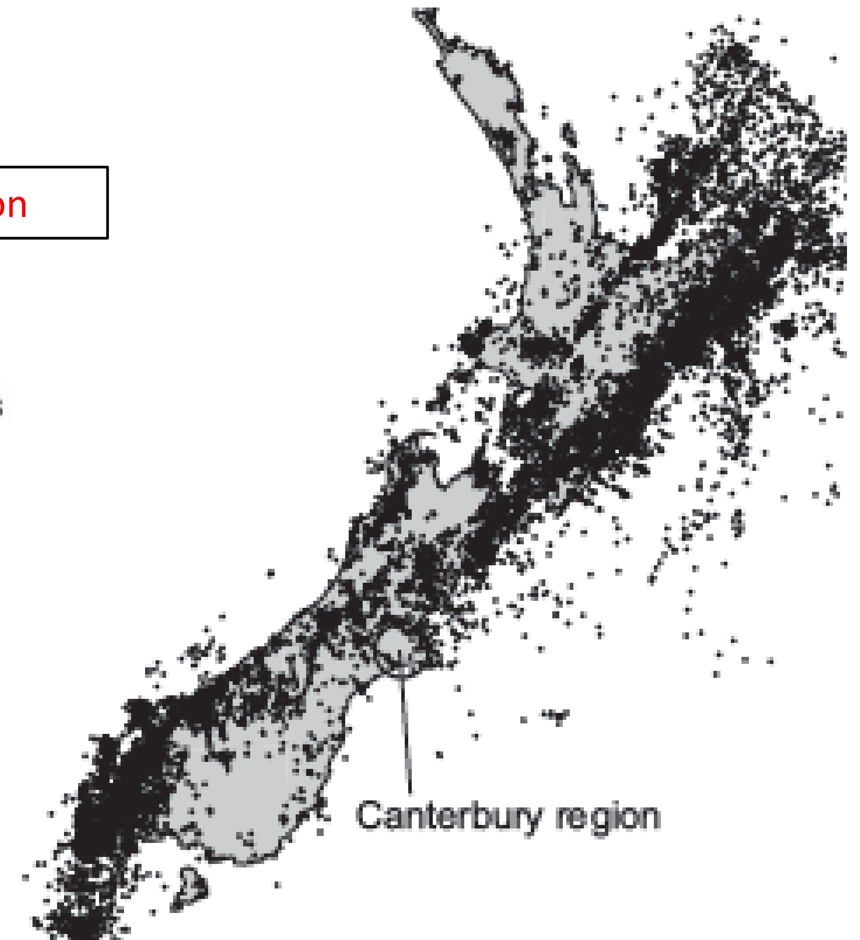
Seismic source characterization

- NZ seismic activity
  - Three dominant tectonic features

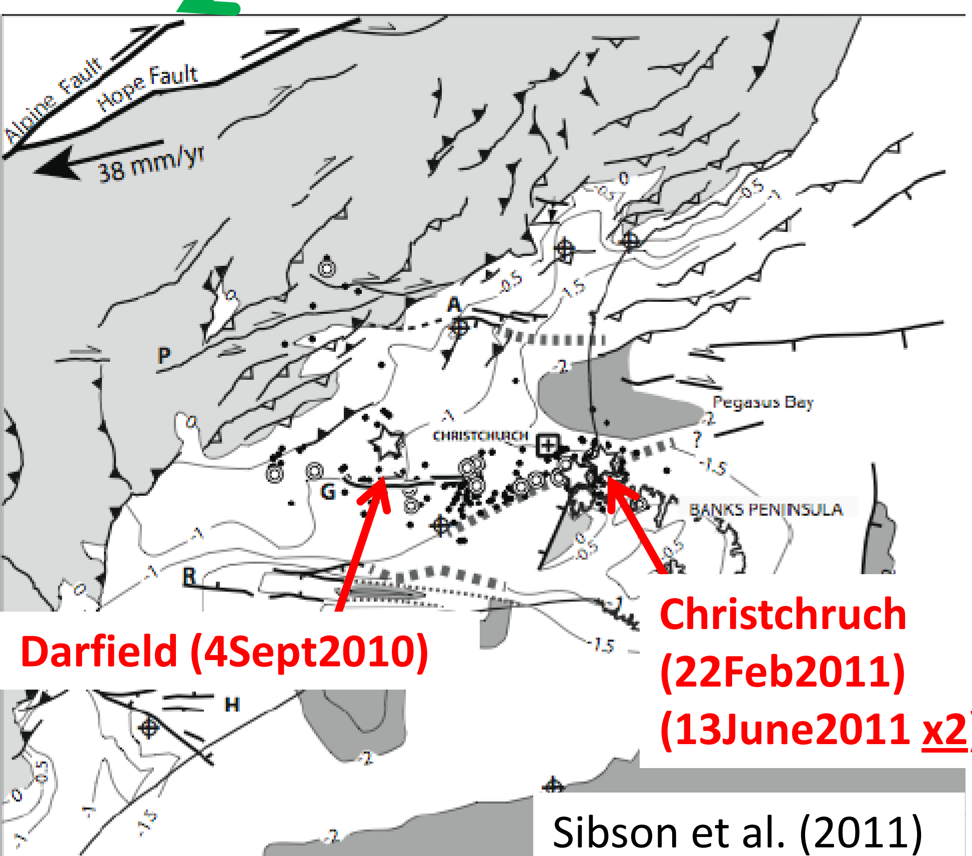


Shallow seismicity (2005-2010)



Seismic source characterization

- Regional tectonic environment
  - ~75% of 38mm/yr plate motion accommodated by Alpine fault (~Mw8.1 every 200-300yrs)



Sibson et al. (2011)

  - ~5mm/yr of distributed deformation within 100km east of Alpine fault
  - Understanding of tectonics in this region limited due to sediment depth
  - M_w up to 7.2 allowed for in background seismicity model

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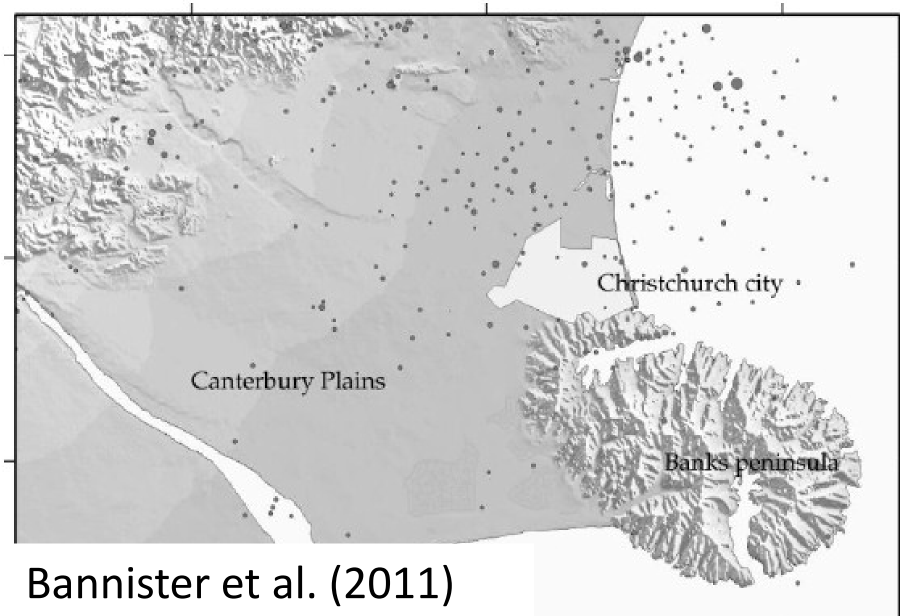
Seismic source characterization

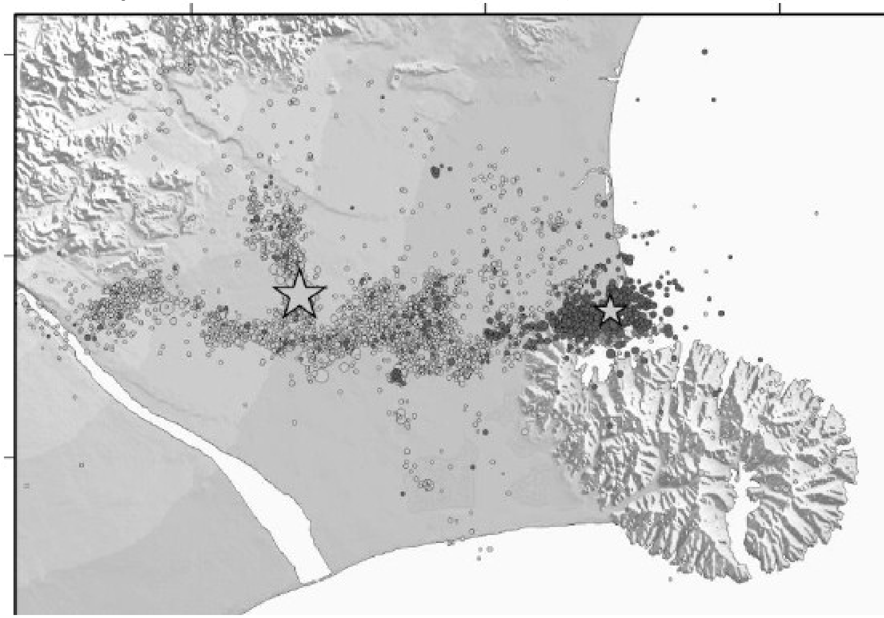
- The Canterbury earthquake sequence

Previous 10 years (Sept 1 2000-2010)



Bannister et al. (2011)

Sept 3 2010 – June 2011 (10 months)



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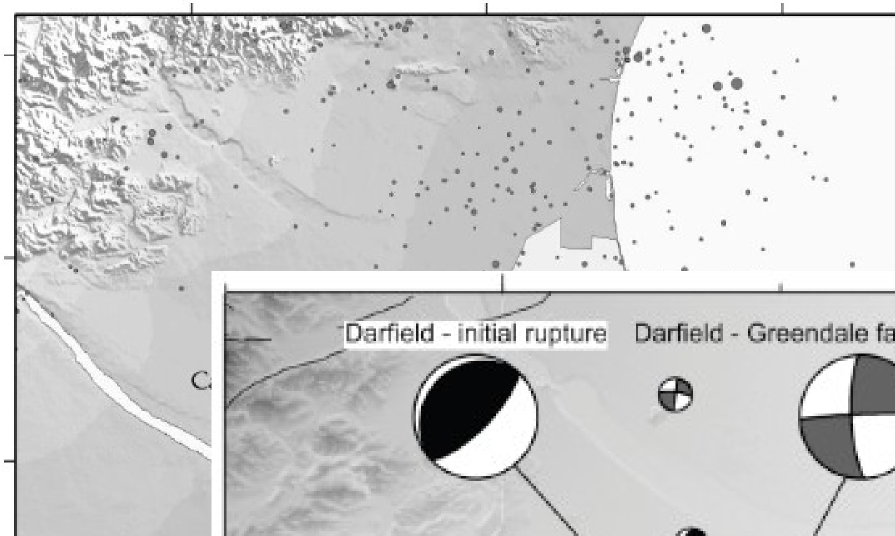

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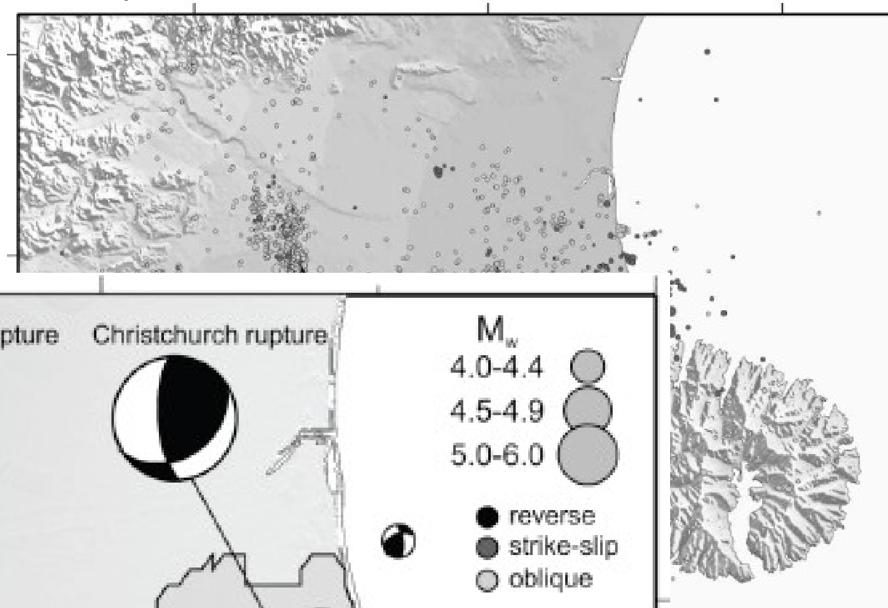
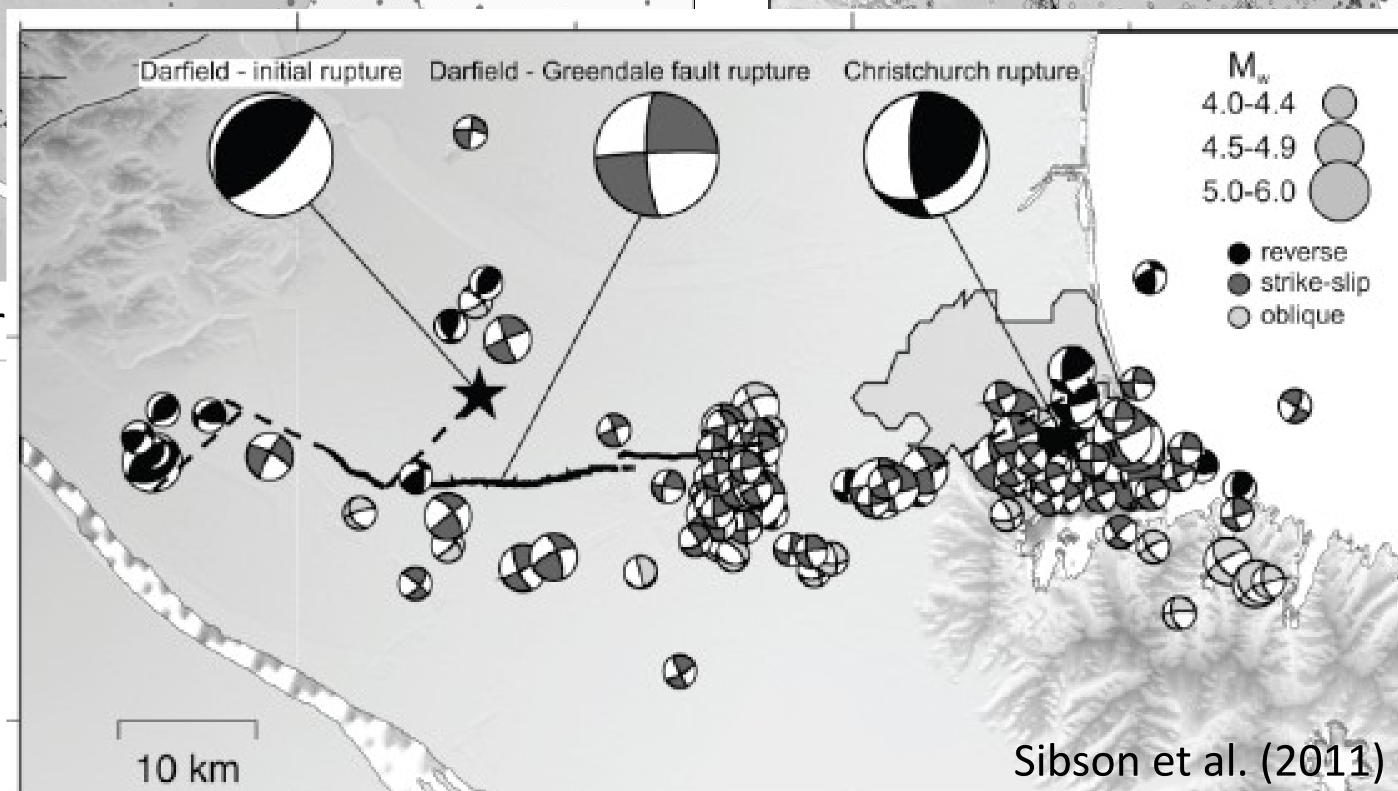


Bannister



Sibson et al. (2011)

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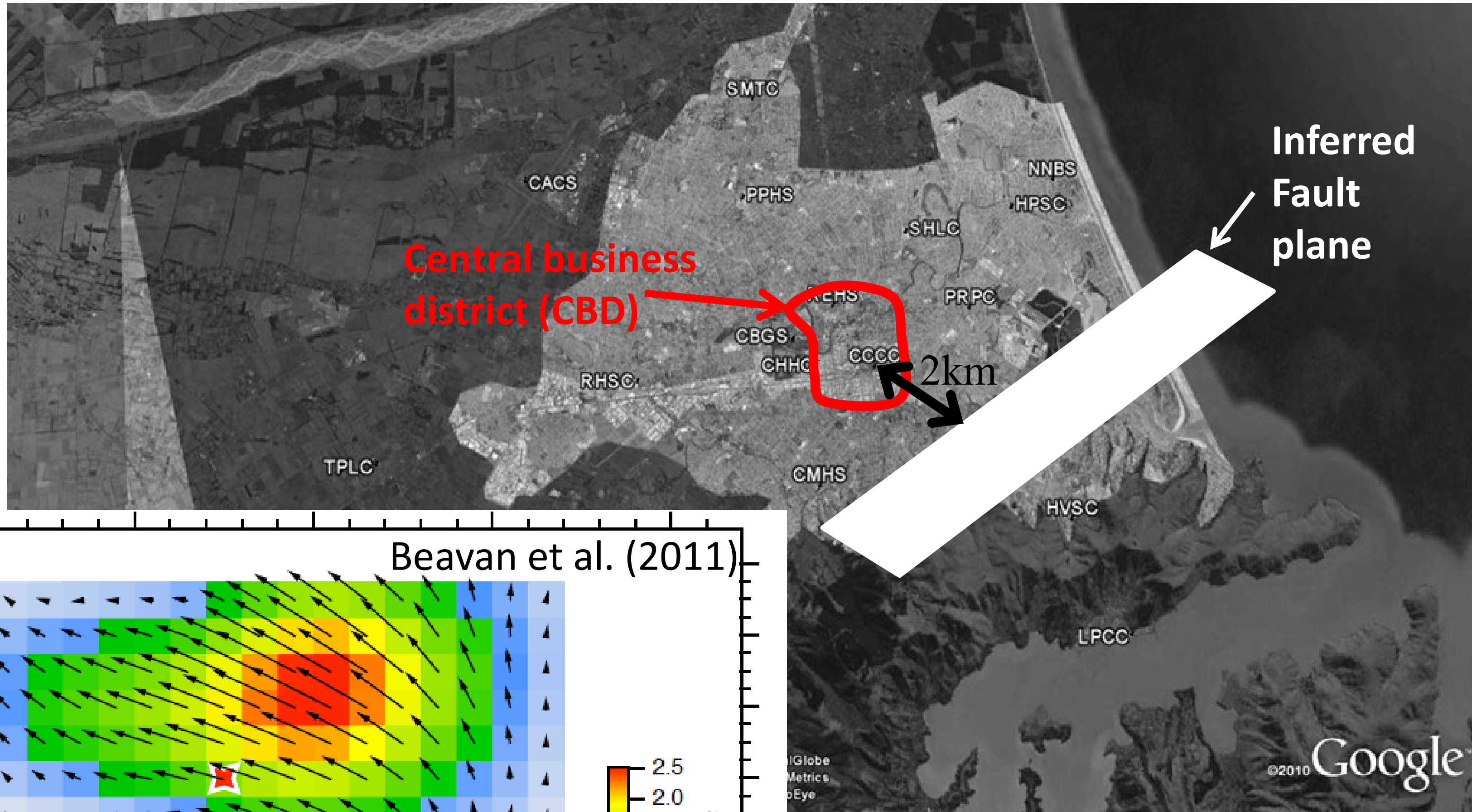

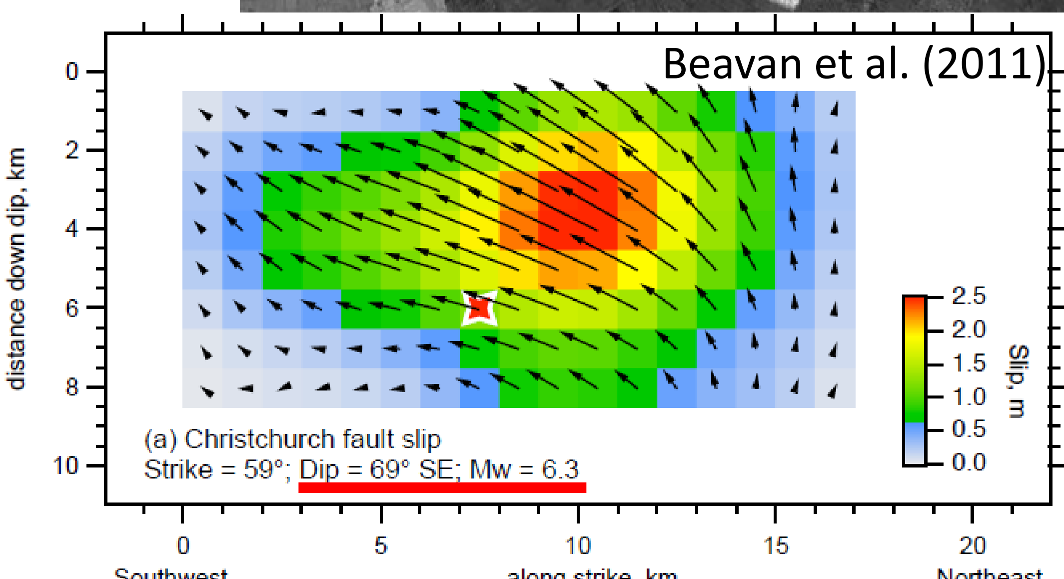

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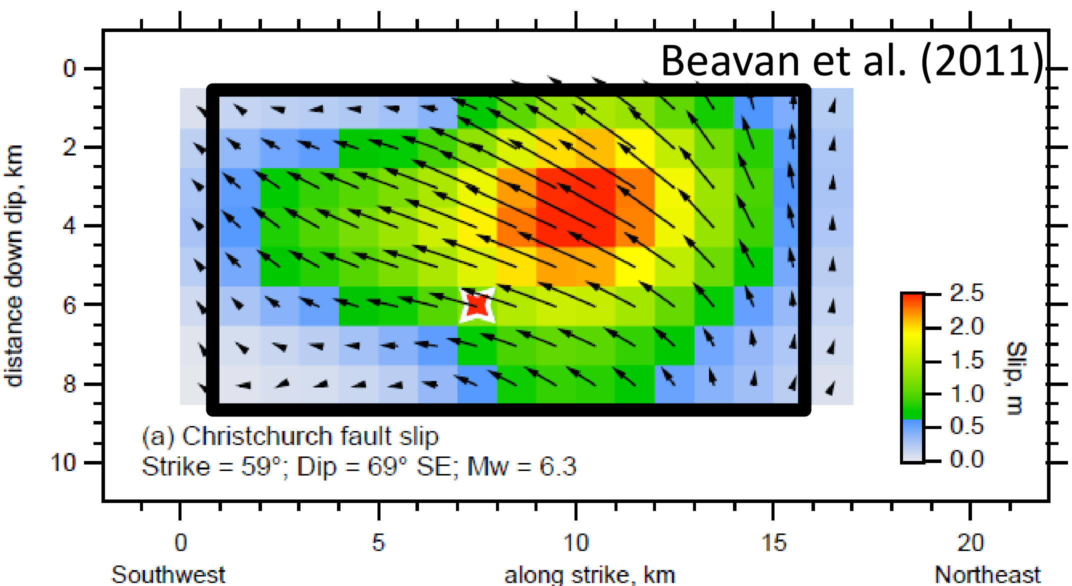
Source characterization

- Finite Fault
  - "Trimmed" using Somerville et al. (1999)
  - Dimensions: 15km along-strike, 8km down-dip
  - M_w=6.2-6.3 [NZ-spec. pred. = 6.35 (Berryman et al. 2001)]
  - Alternatively, Wells and Coppersmith (1994) predict L=15-17km and W=8.5-9.4km
  - However, Me=6.75 so relatively strong high frequency energy, consistent with the inferred long recurrence interval



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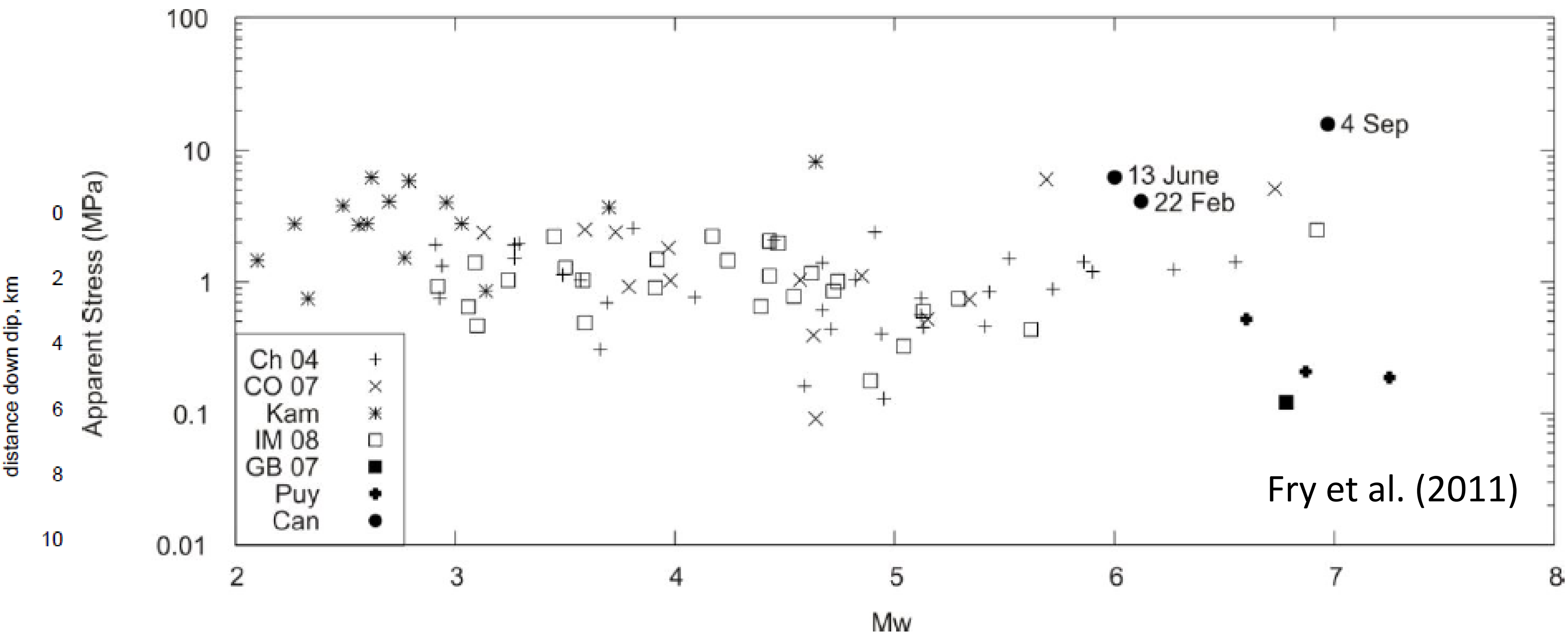

Fry et al. (2011)

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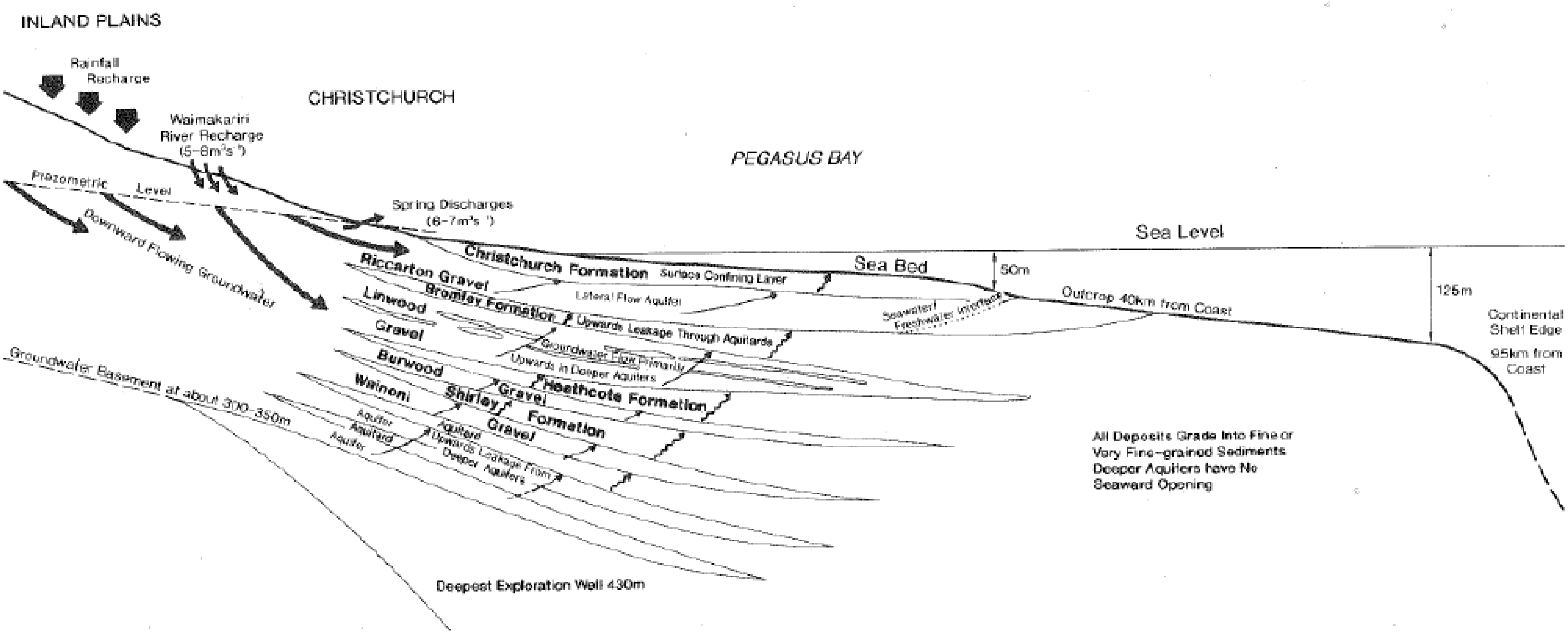
Christchurch geological formations

- Sedimentary geology dominated by fluvial processes with inter-bedded layers of gravels, sands/silts, peat forming aquifers, aquicludes



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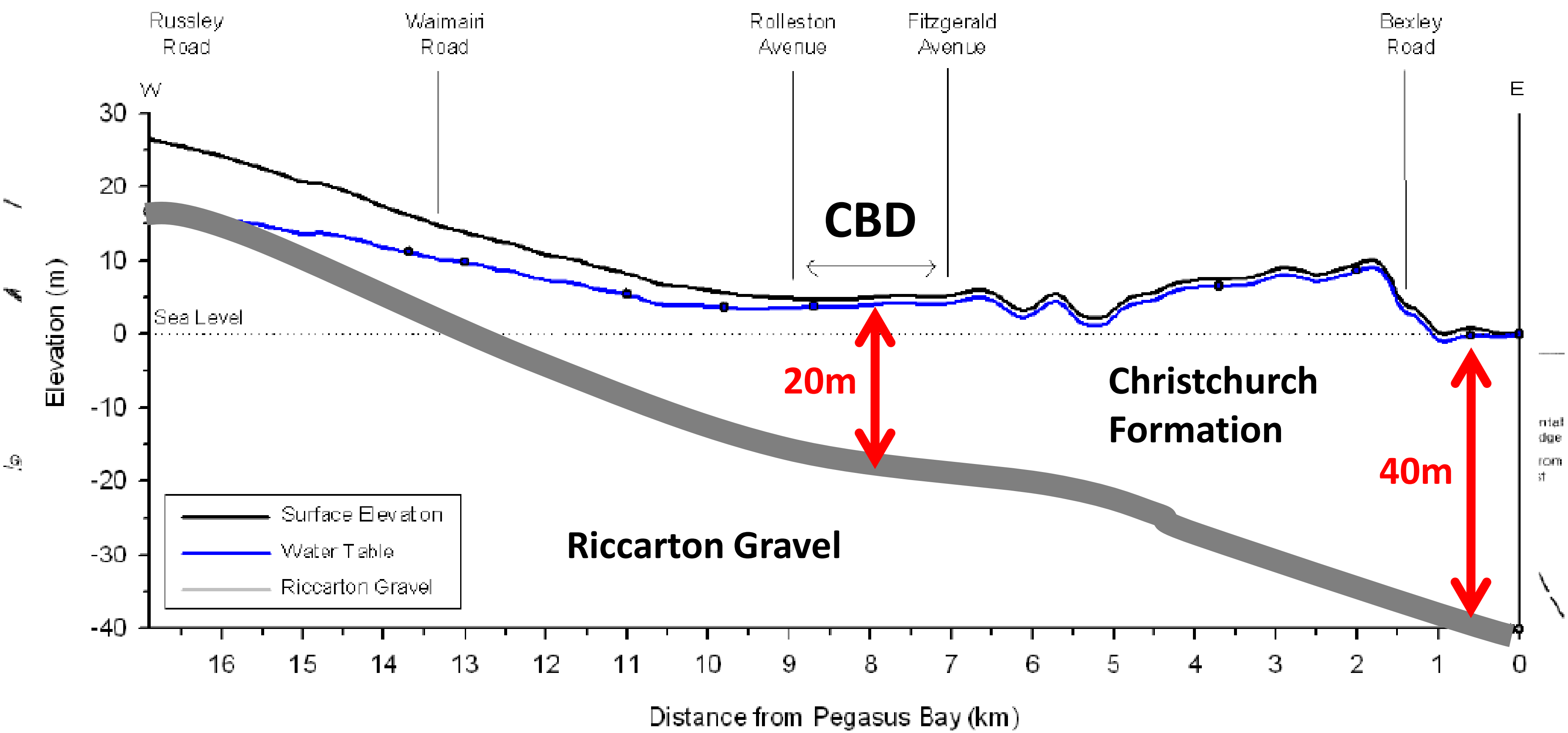
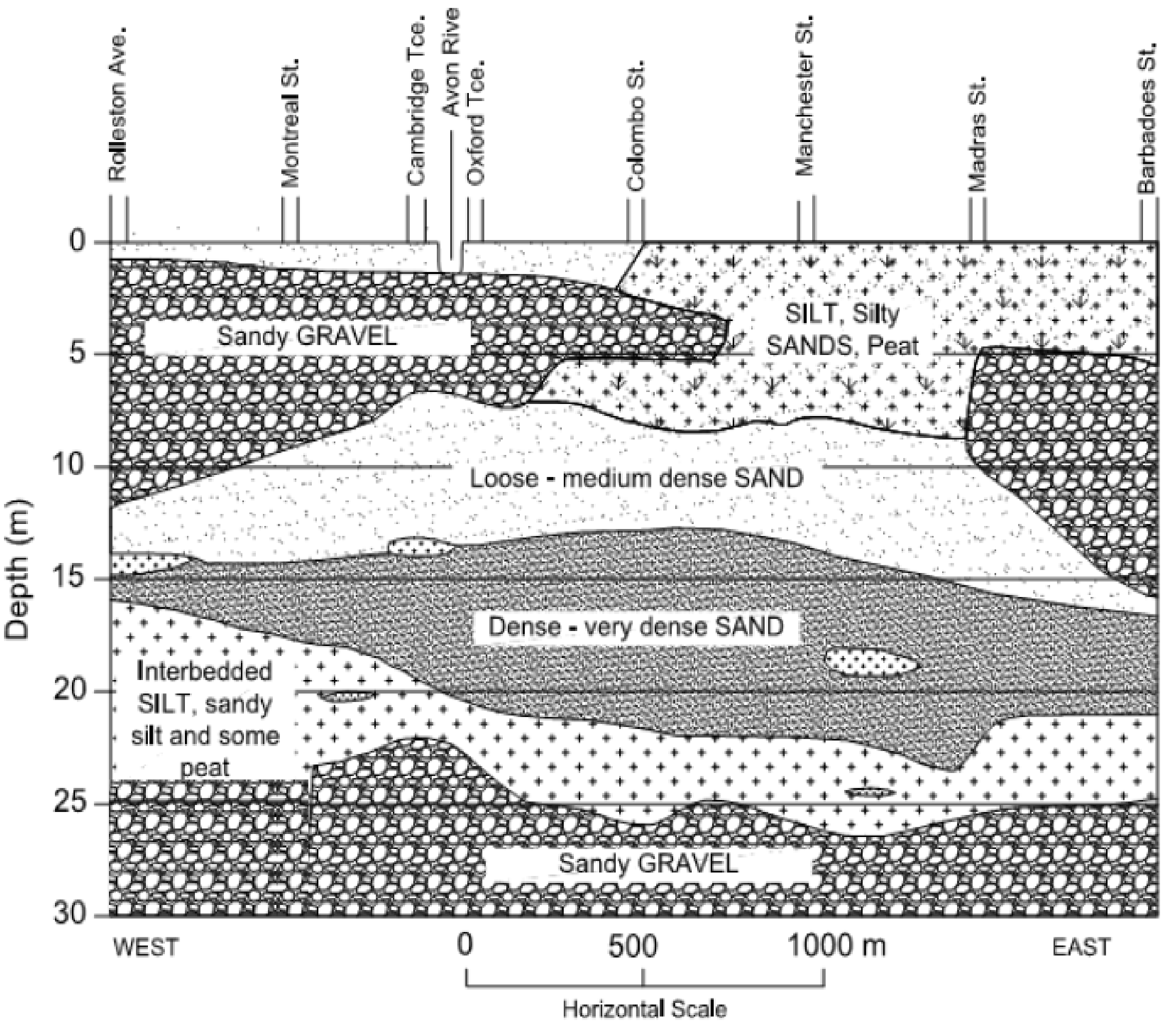
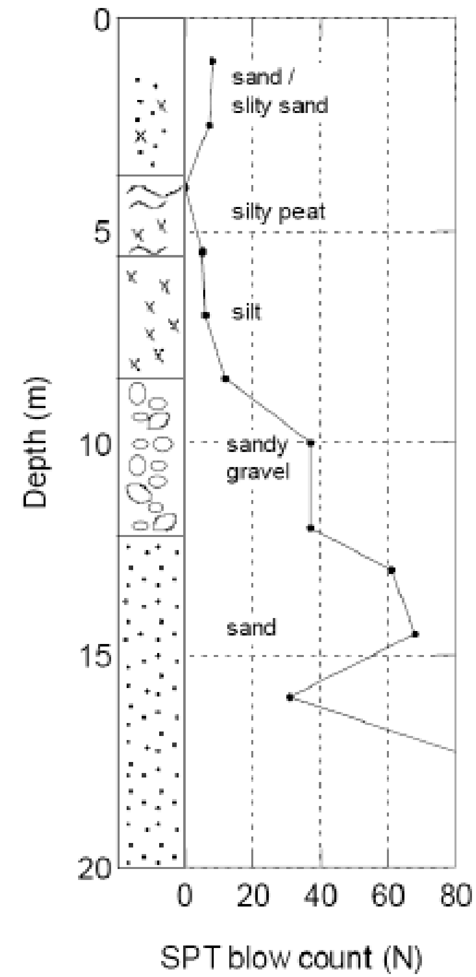


Local surface geology in CBD

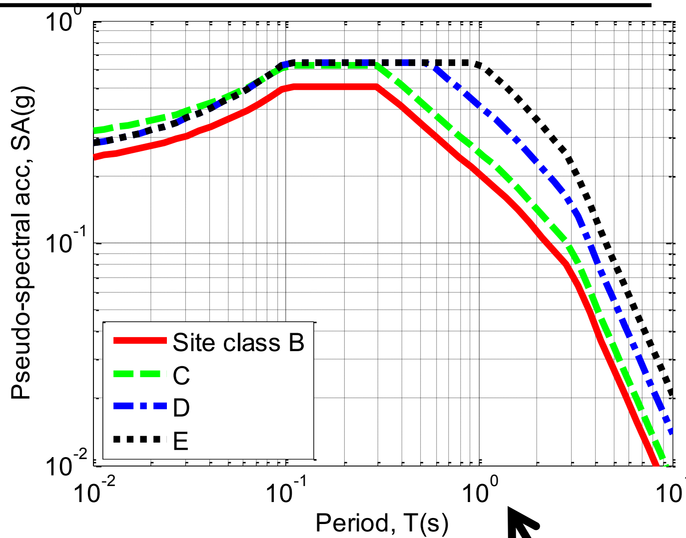
- Highly variable in horizontal and vertical direction, even in simplified view below

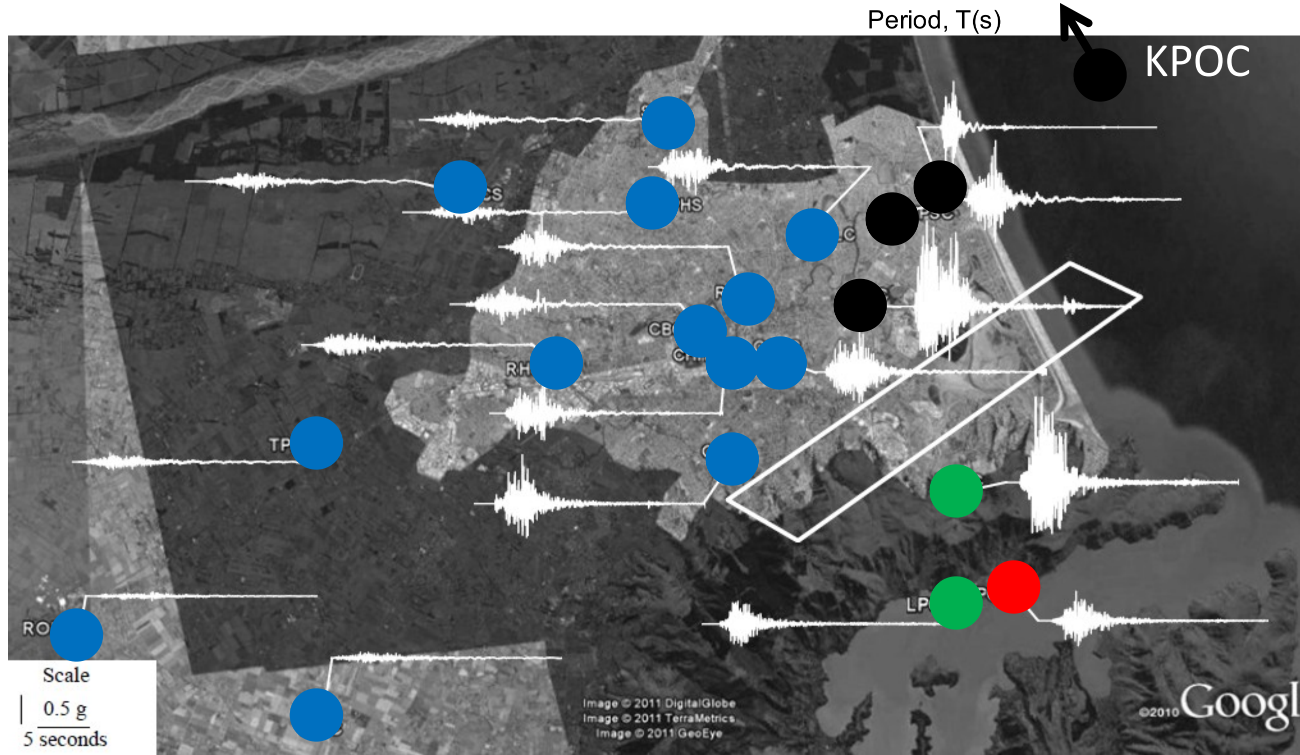




Local geology/soils

- The majority of Christchurch is designated as site class D soil conditions due to the basin depth –
- i.e. not based on surficial geology
- e.g. SM stations
  - B: 1
  - C: 2
  - D: 13
  - E: 4

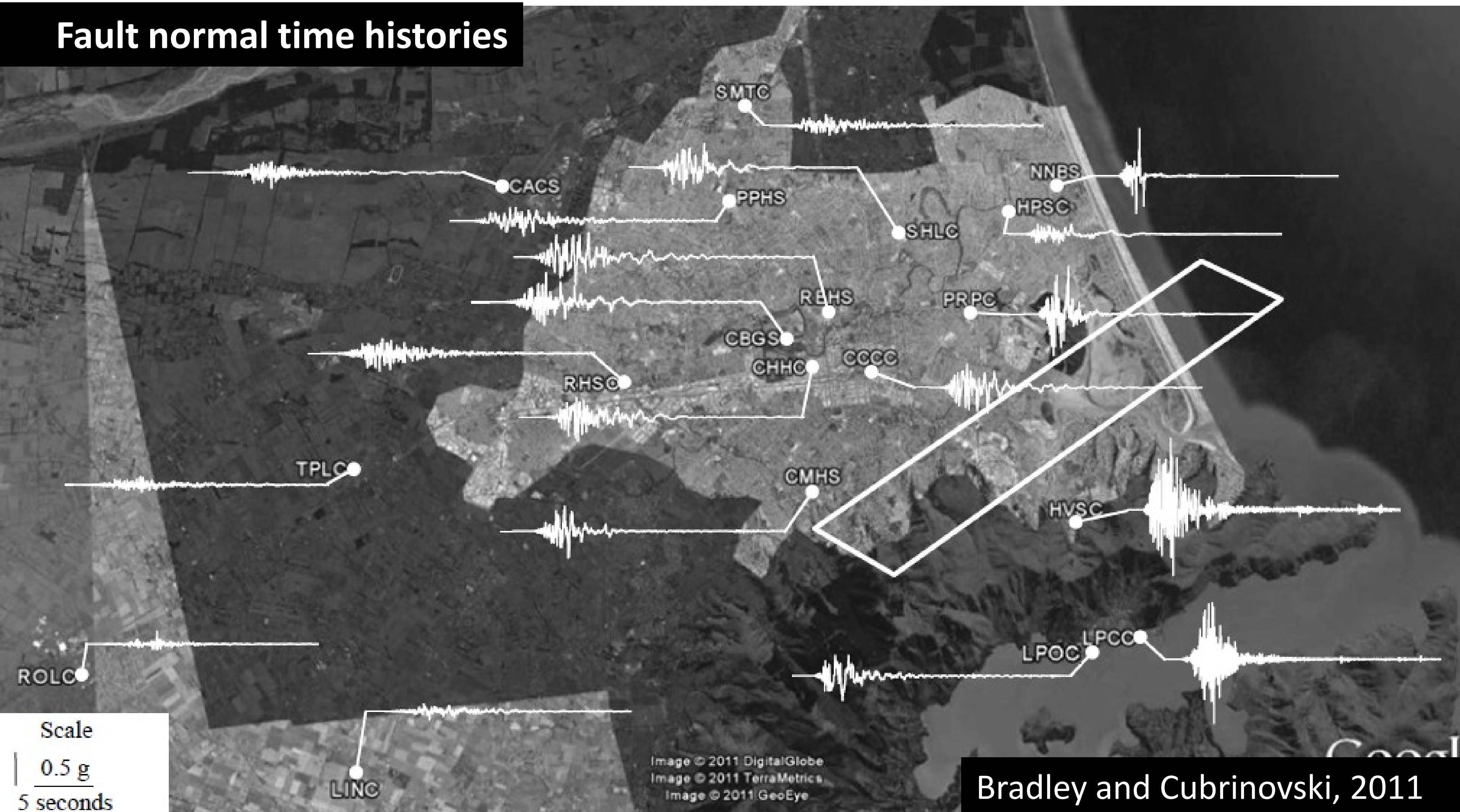




Ground motion characterization

- 20 ground motion stations within 20km of the source, 14 of which are within 10km
- Maximum values: horizontal PGA =1.41g, vertical PGA=2.21g, horizontal PGV=81cm/s
- 9 stations with horizontal PGAs above 0.4g

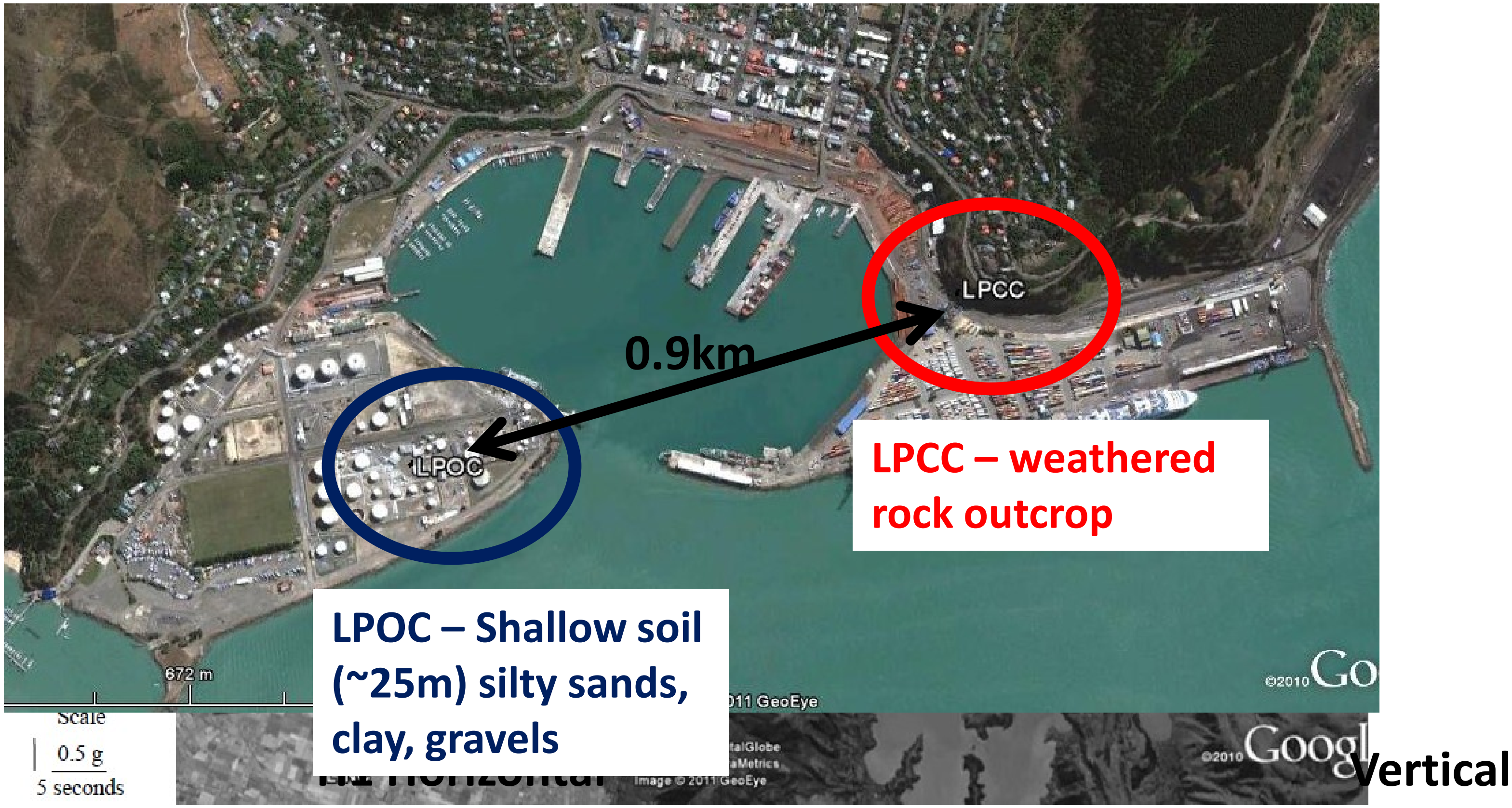
Fault normal time histories



Bradley and Cubrinovski, 2011

Ground motion characterization

- Response on soil and rock sites



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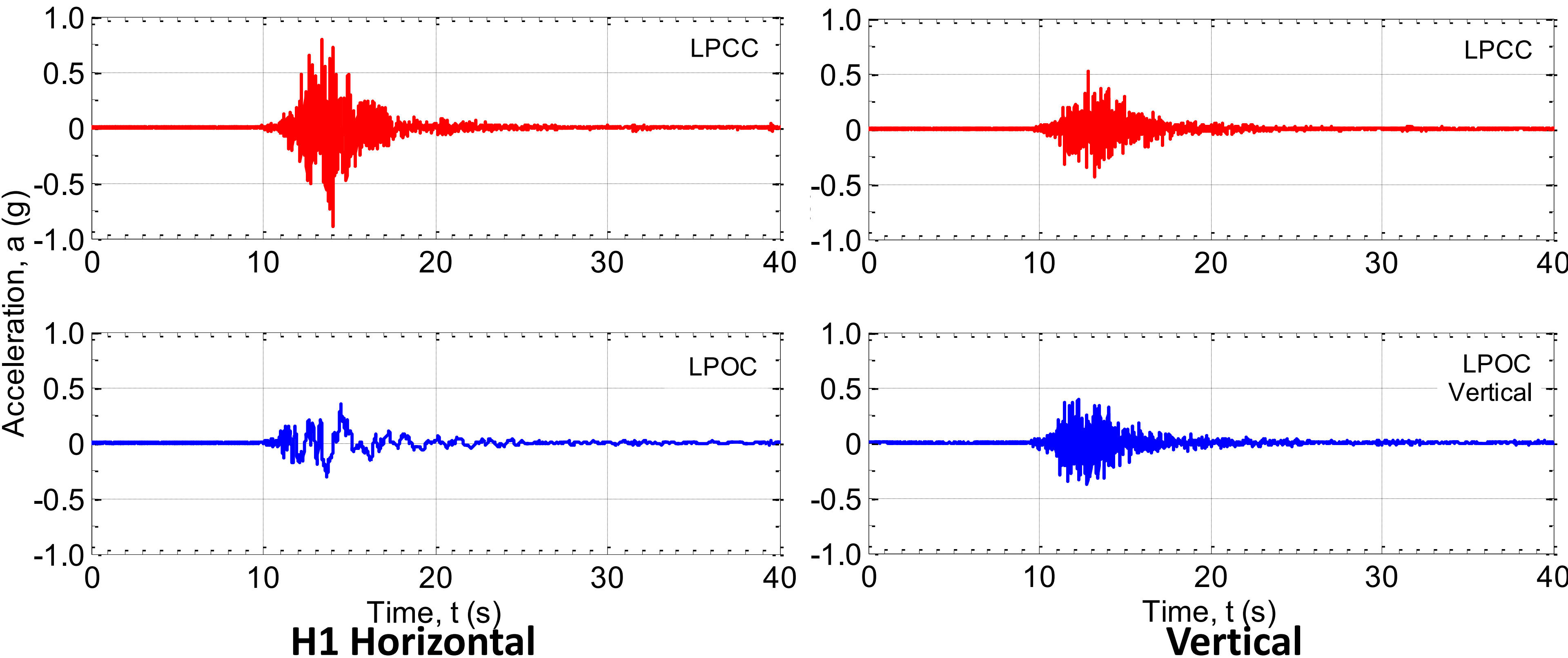

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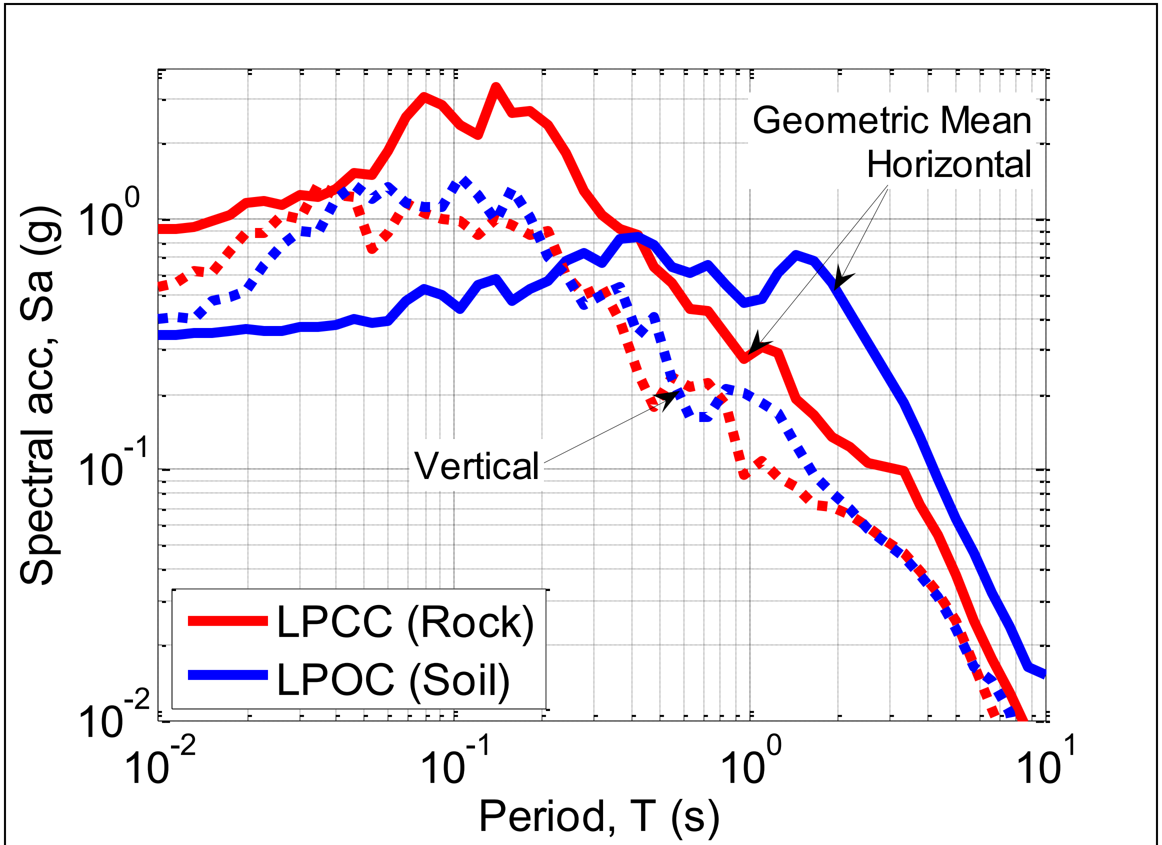

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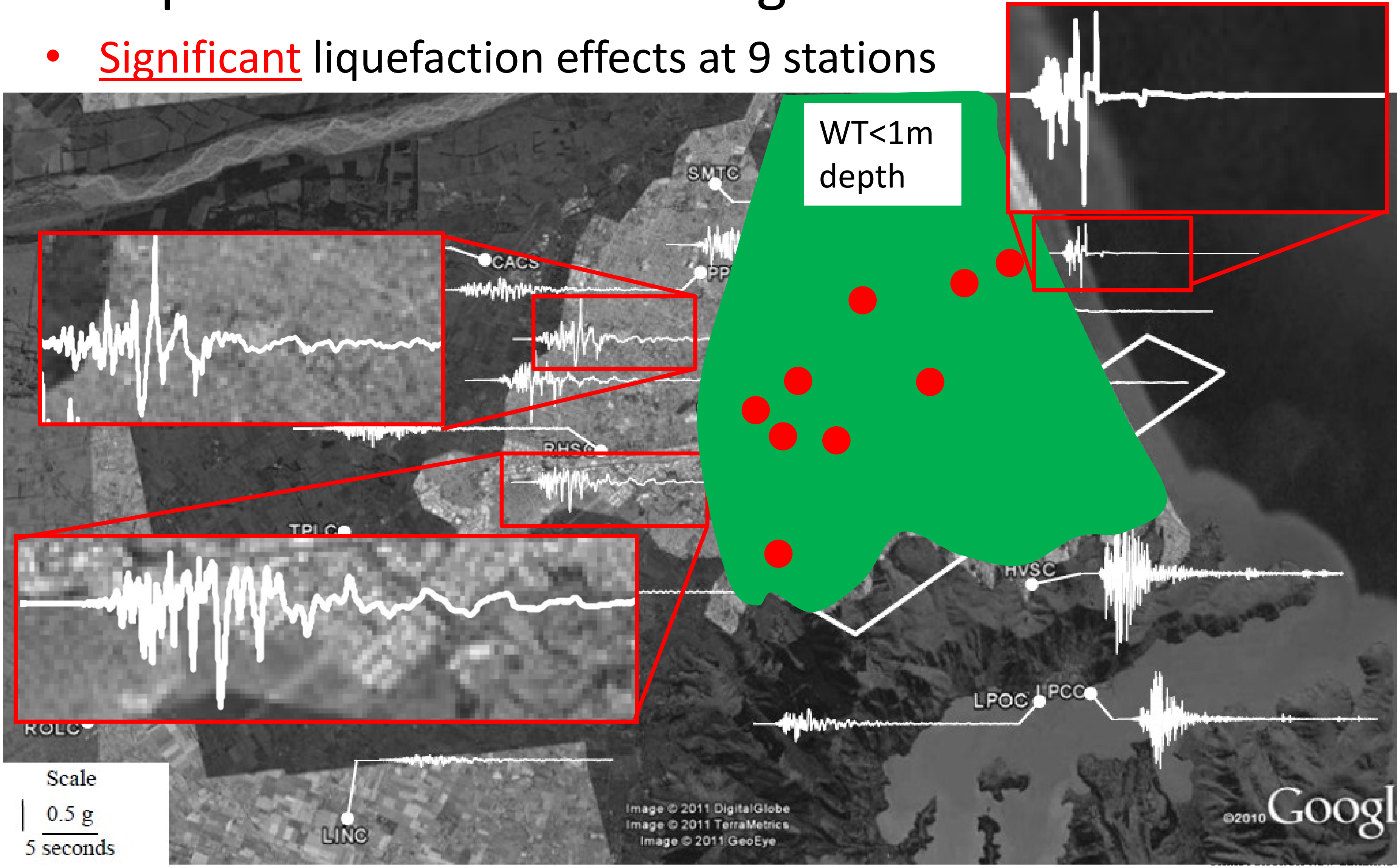
Ground motion characterization

- Liquefaction in observed ground motions
- Significant liquefaction effects at 9 stations



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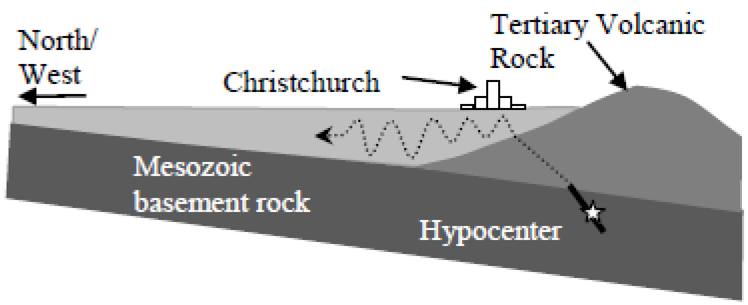
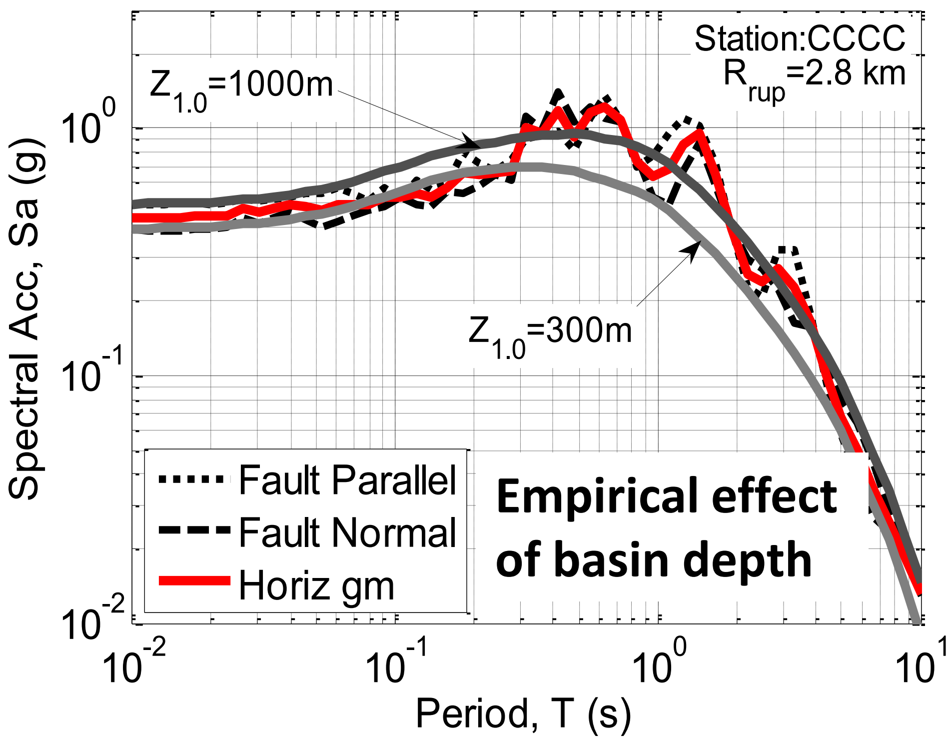
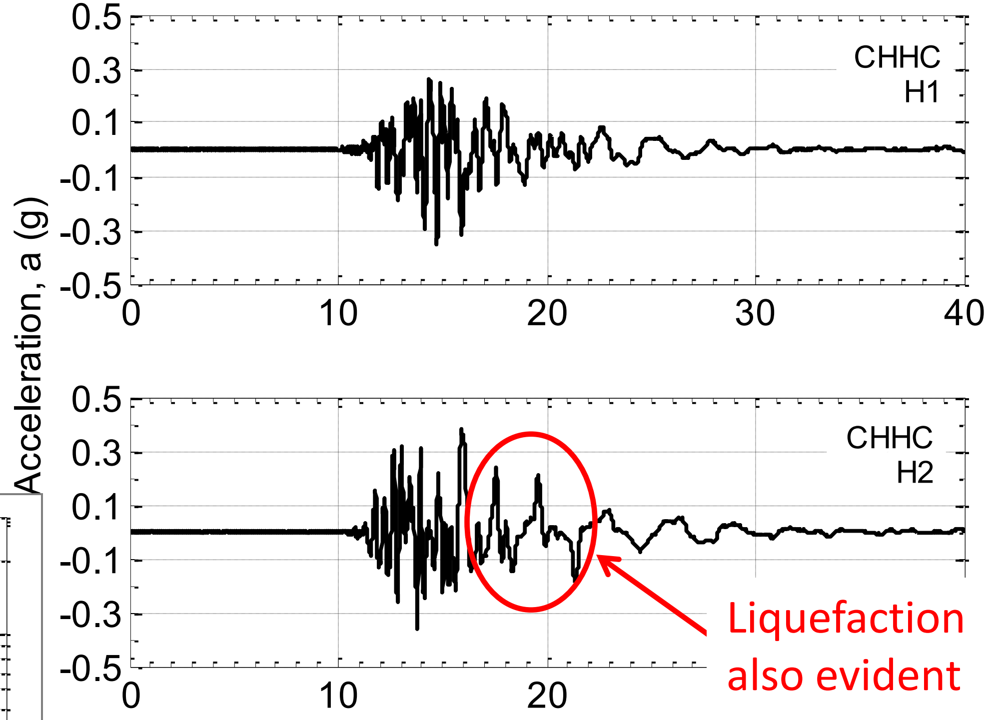
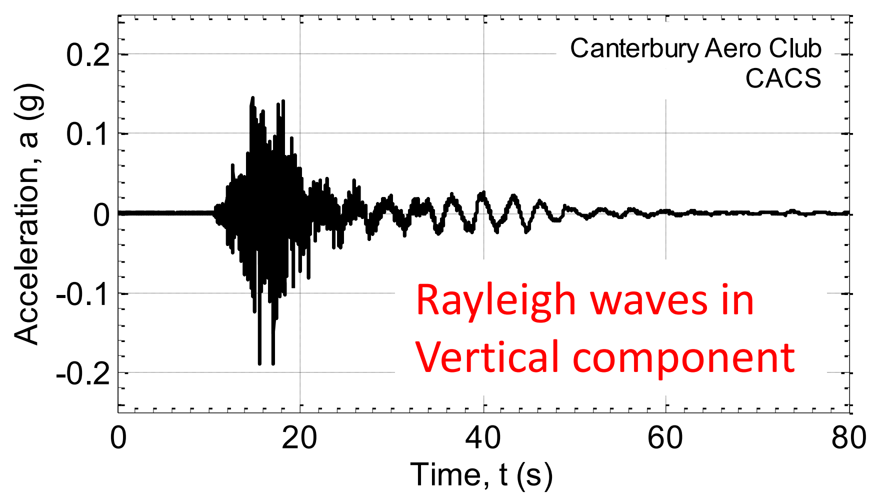
Ground motion characterization

- Basin effects



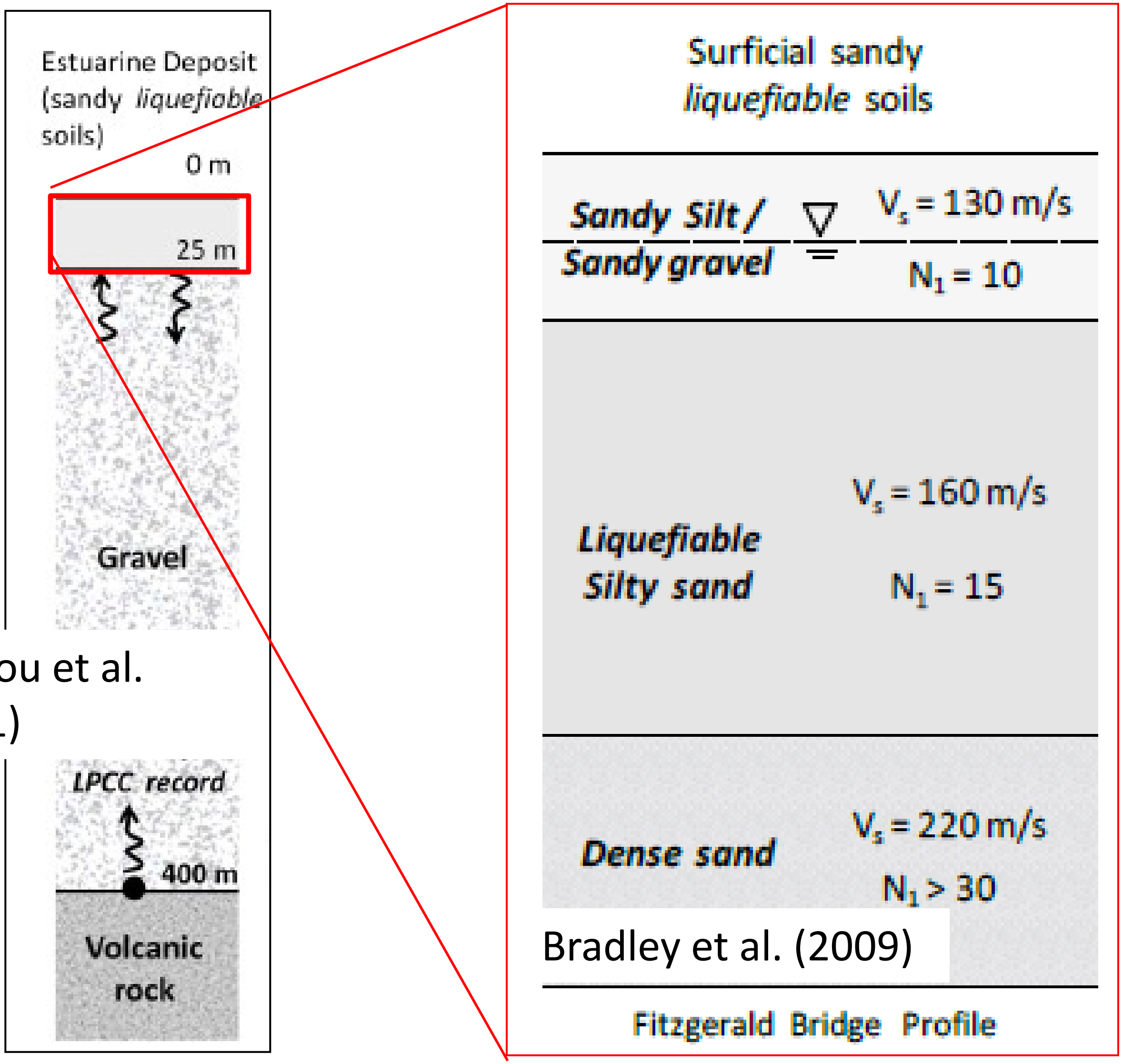






Ground motion characterization

- Site and liquefaction effects in modelling



Smyrou et al. (2011)

Bradley et al. (2009)

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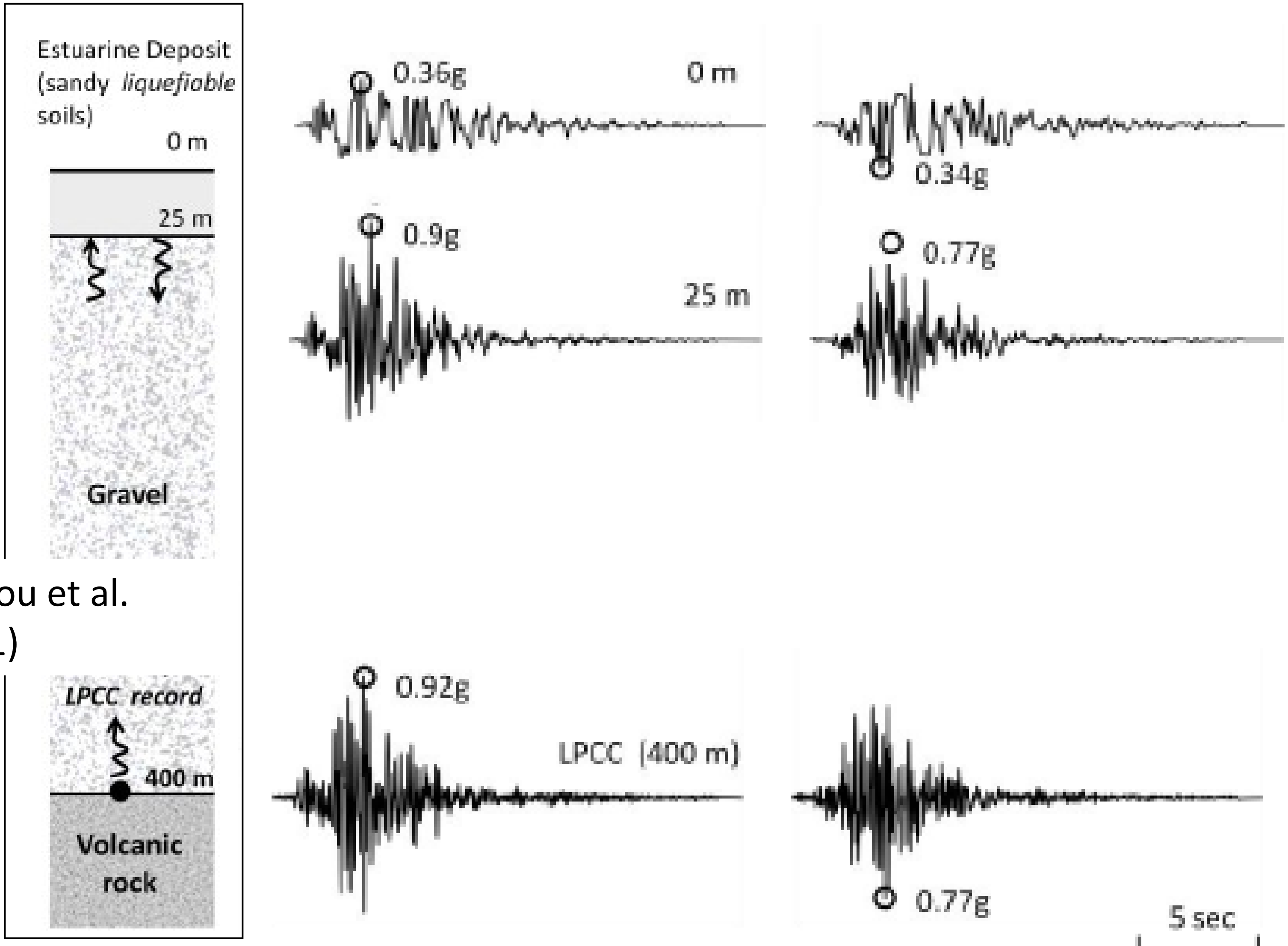

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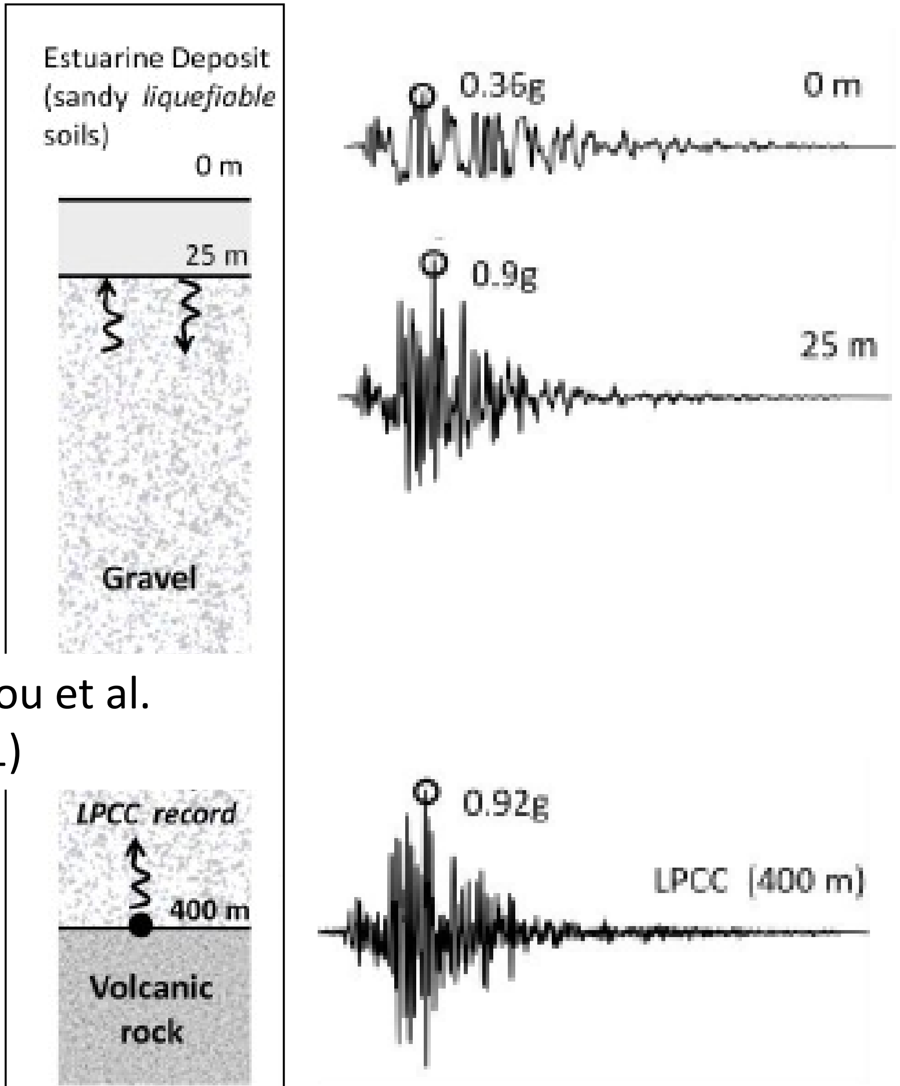
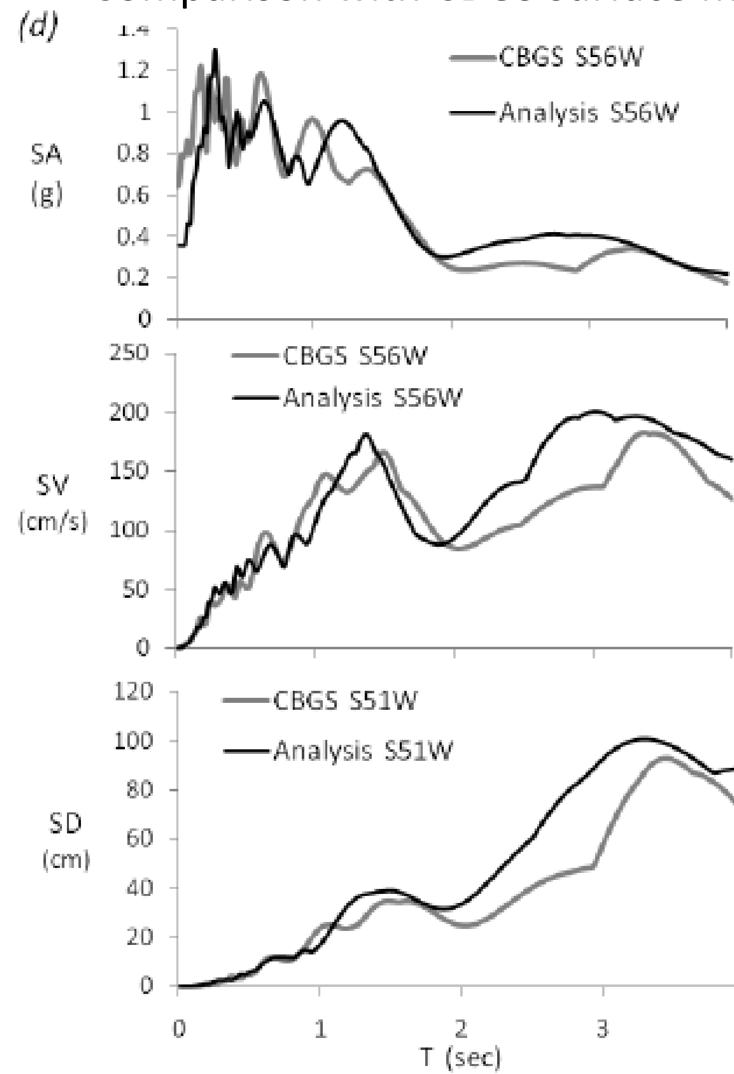


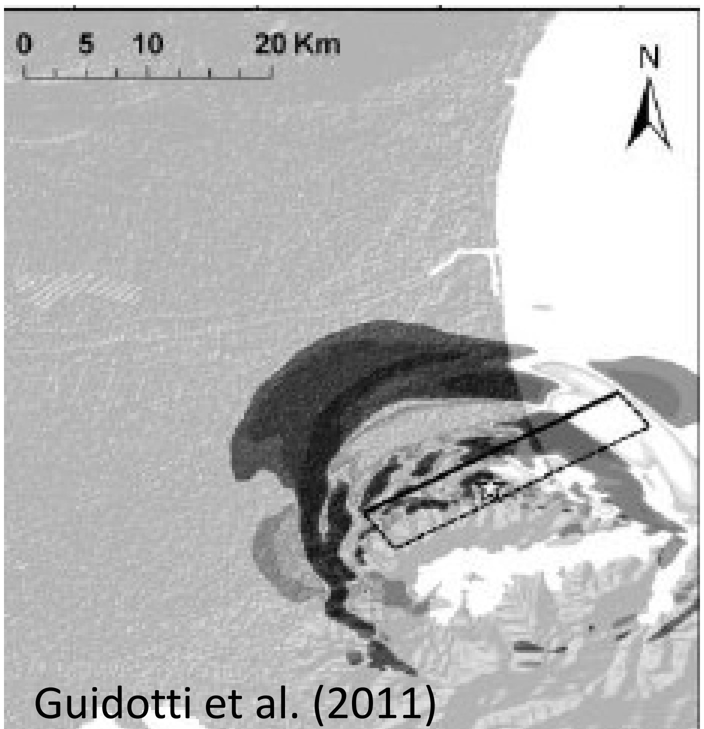
Smyrou et al. (2011)

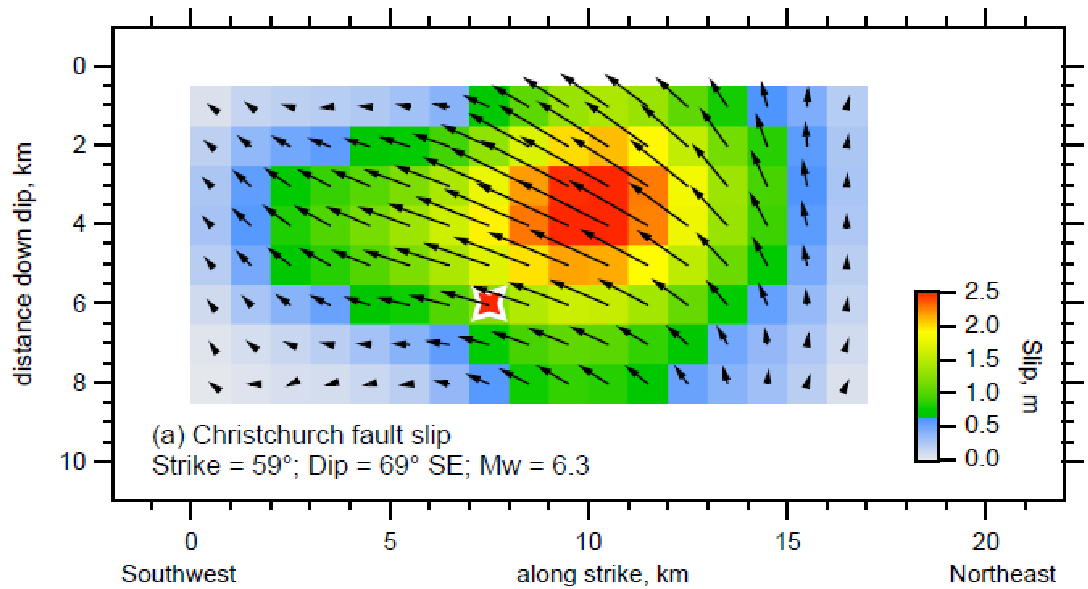
Comparison with CBGS surface motion



Ground motion characterization

- Importance of forward-directivity effects
  - A relatively homogenous slip distribution suggests significant directivity (Beavan et al (2011), Holden (2011) , Guidotti et al. (2011))
  - However more heterogeneous rupture suggests directivity effect not as pronounced over a wide area





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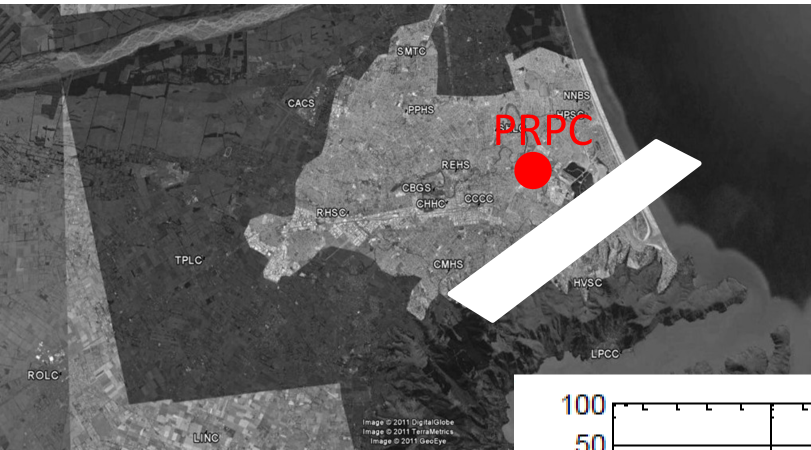
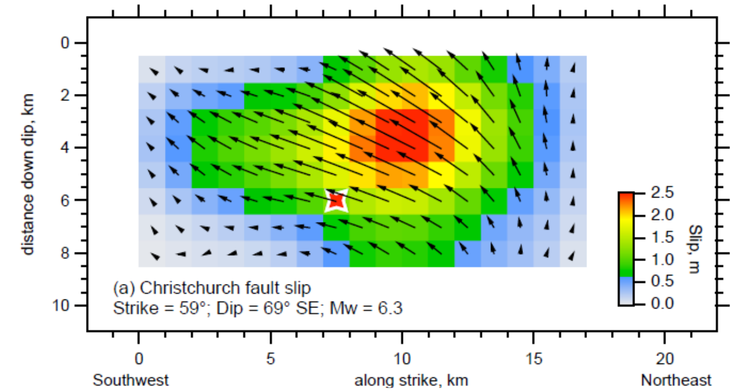
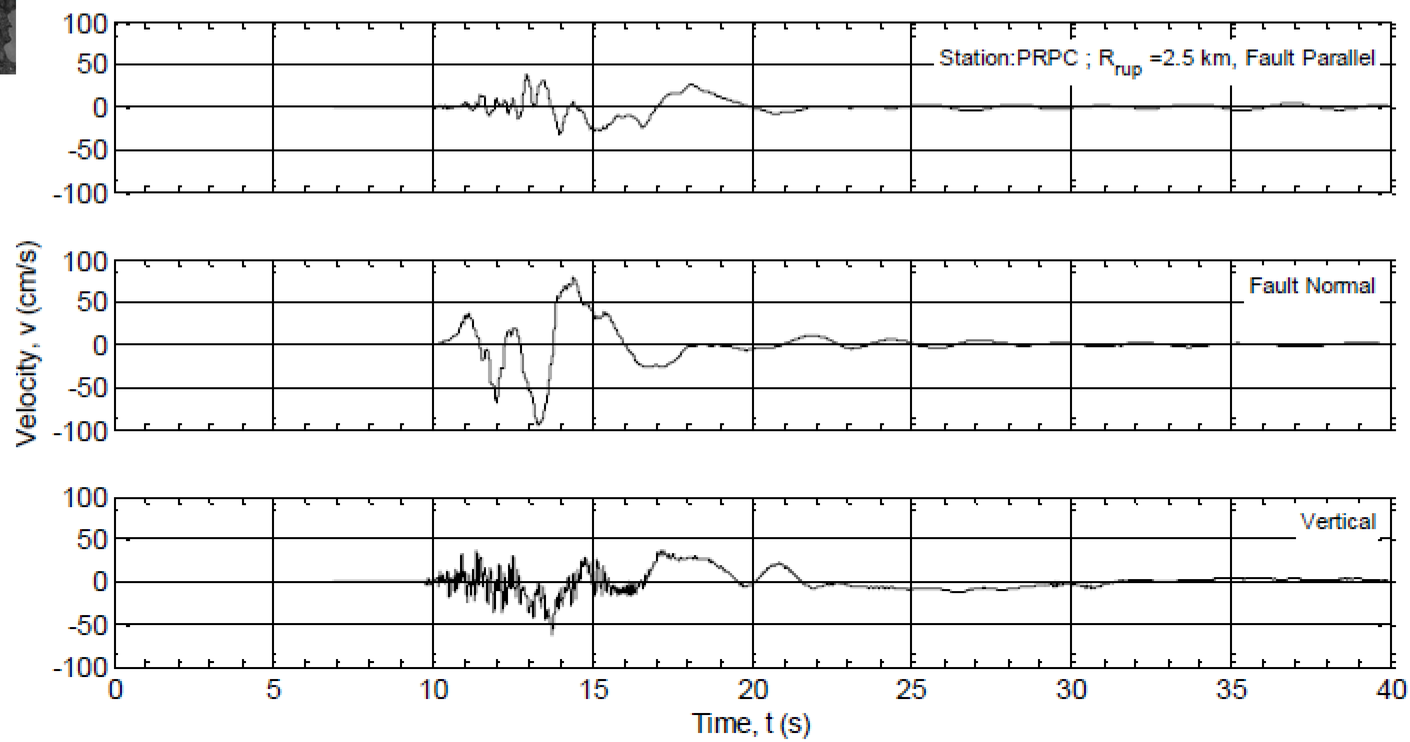
Ground motion characterization

- Observed Forward directivity effects - PRPC

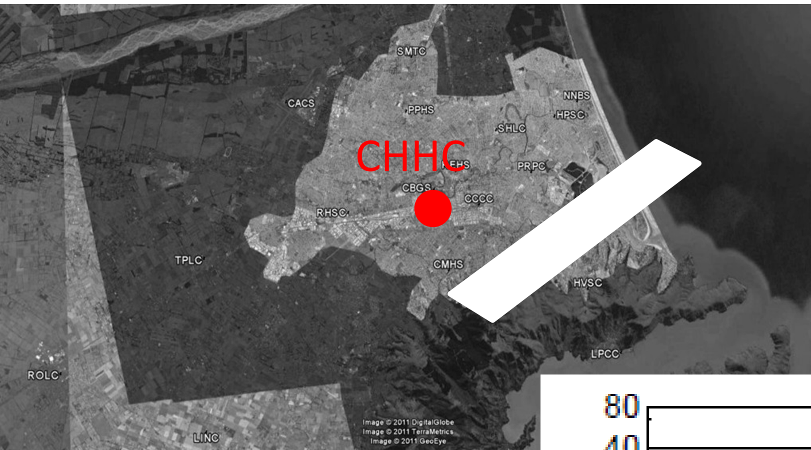


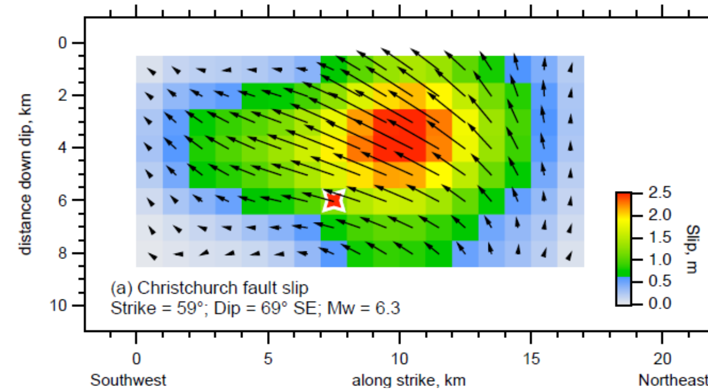


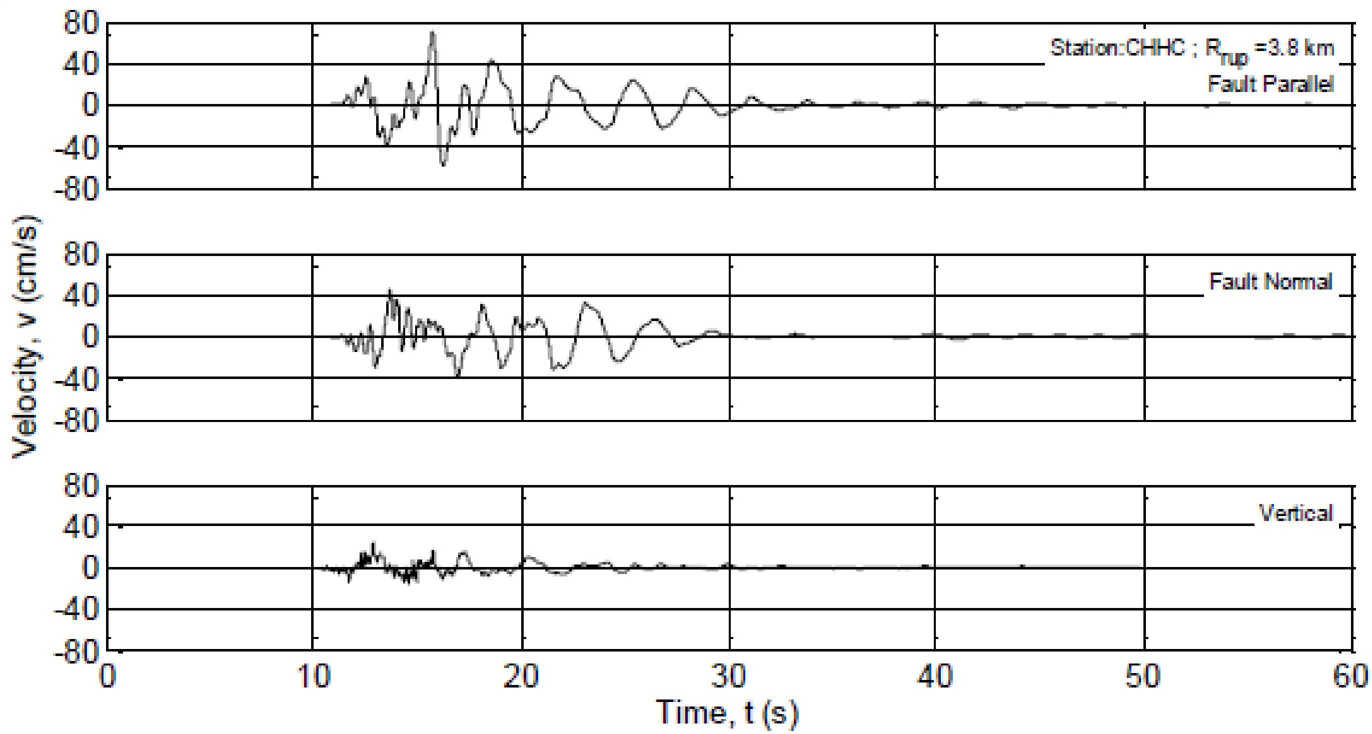


Ground motion characterization

- Forward directivity effects - CHHC







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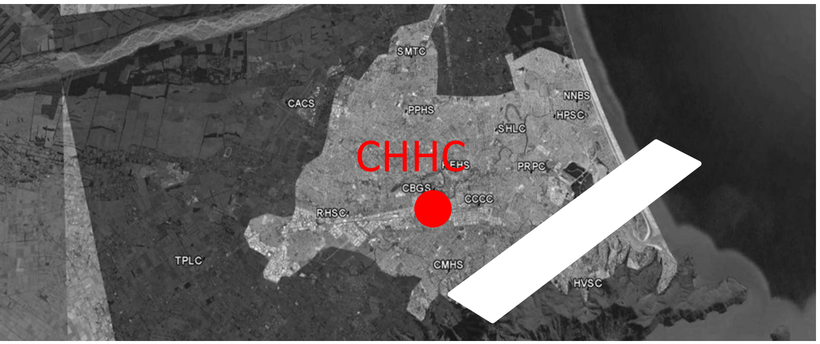
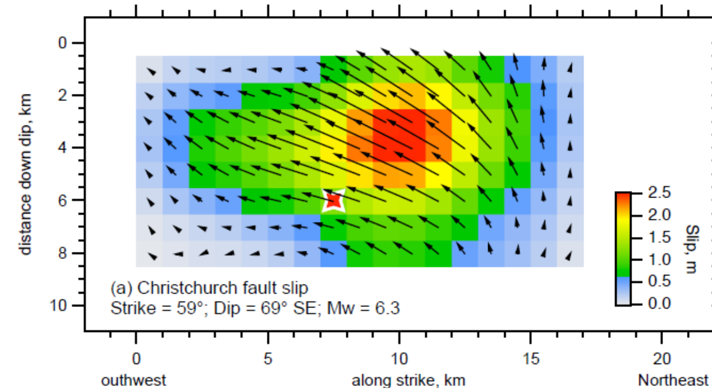
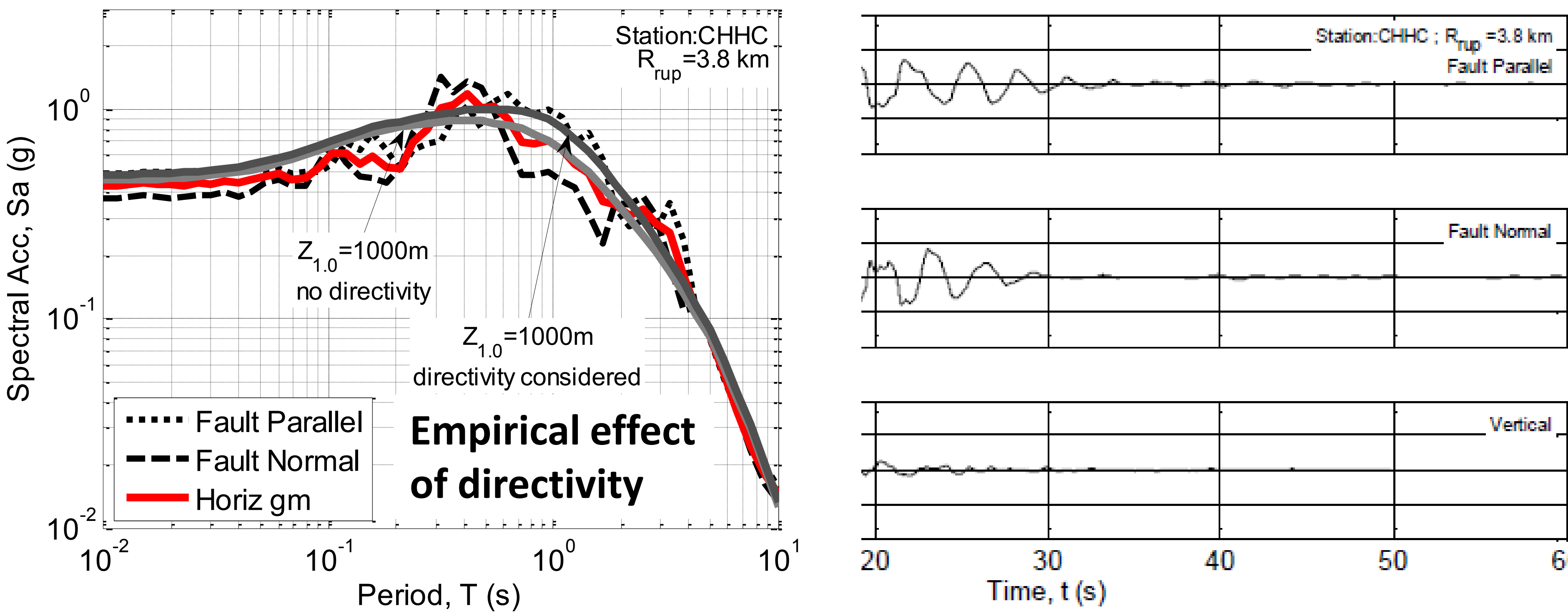
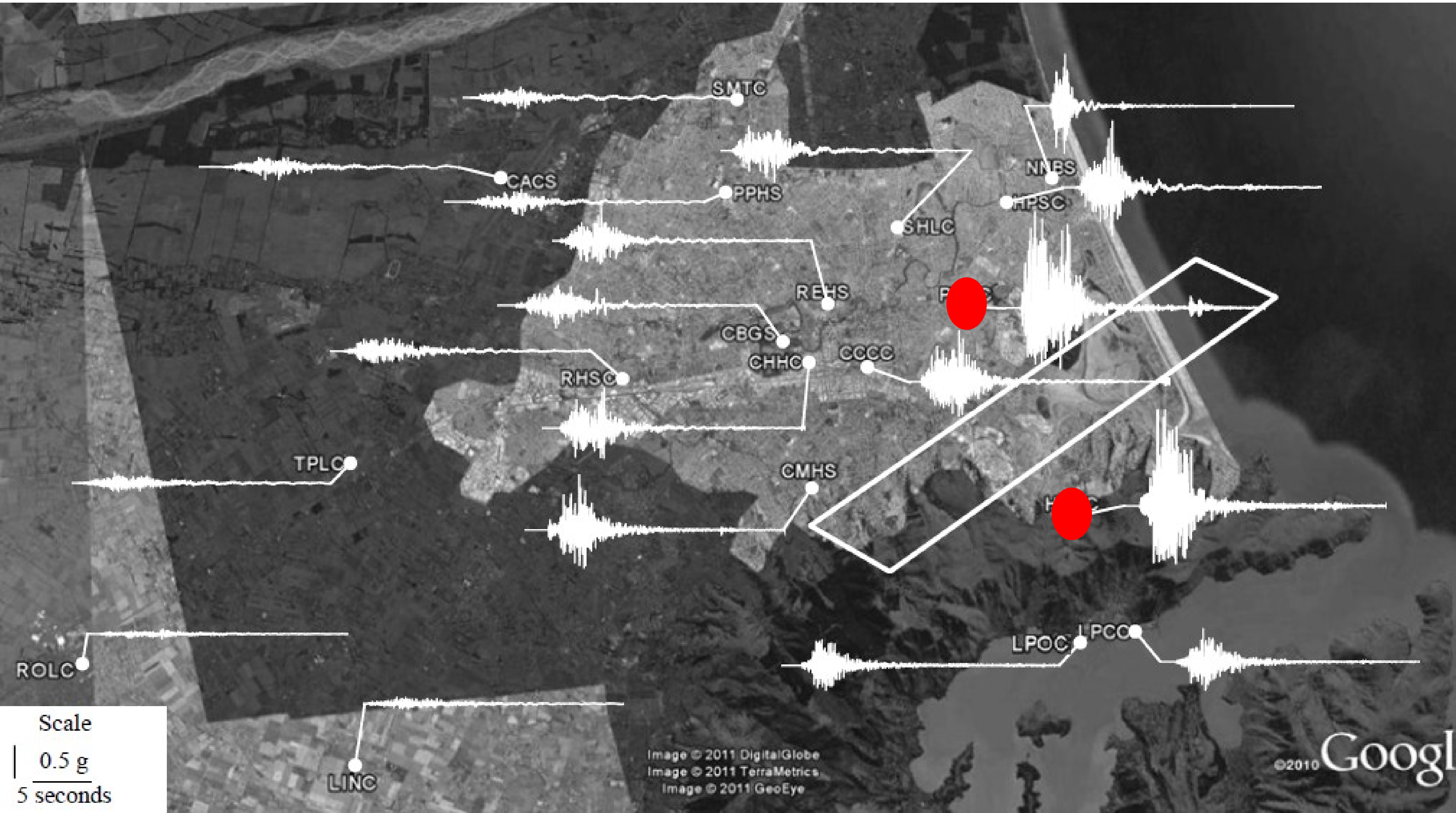






Ground motion characterization

- Large vertical accelerations observed (10 PGA_v>0.5g)
  - Anticipated: steep fault dip (69deg), SV->P conversions



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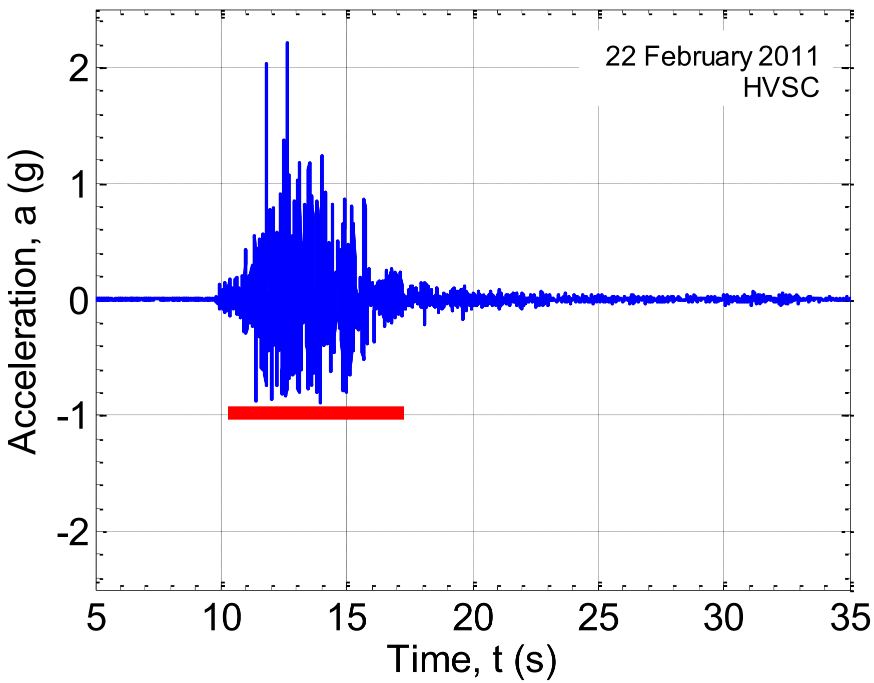
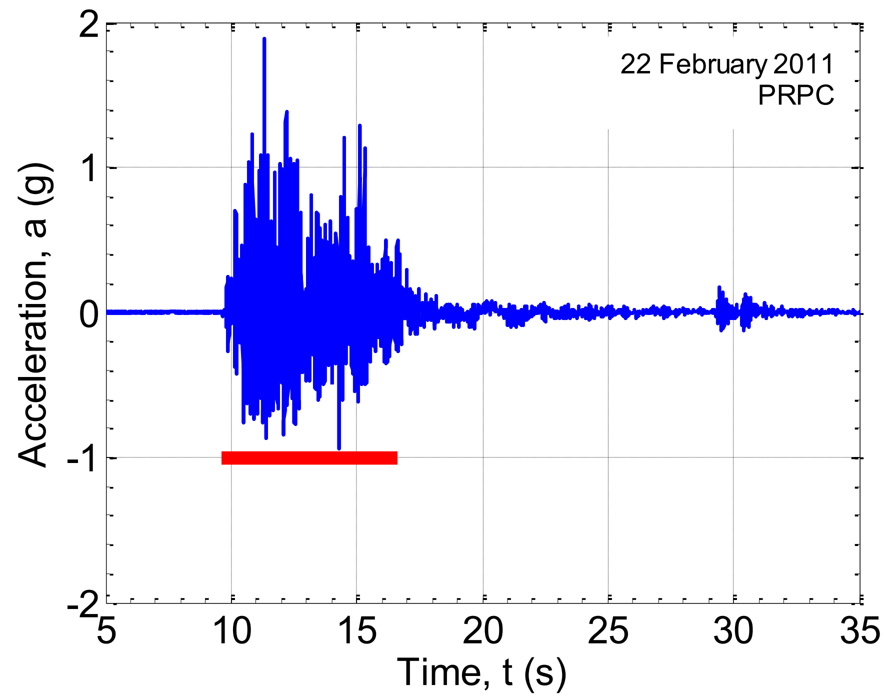




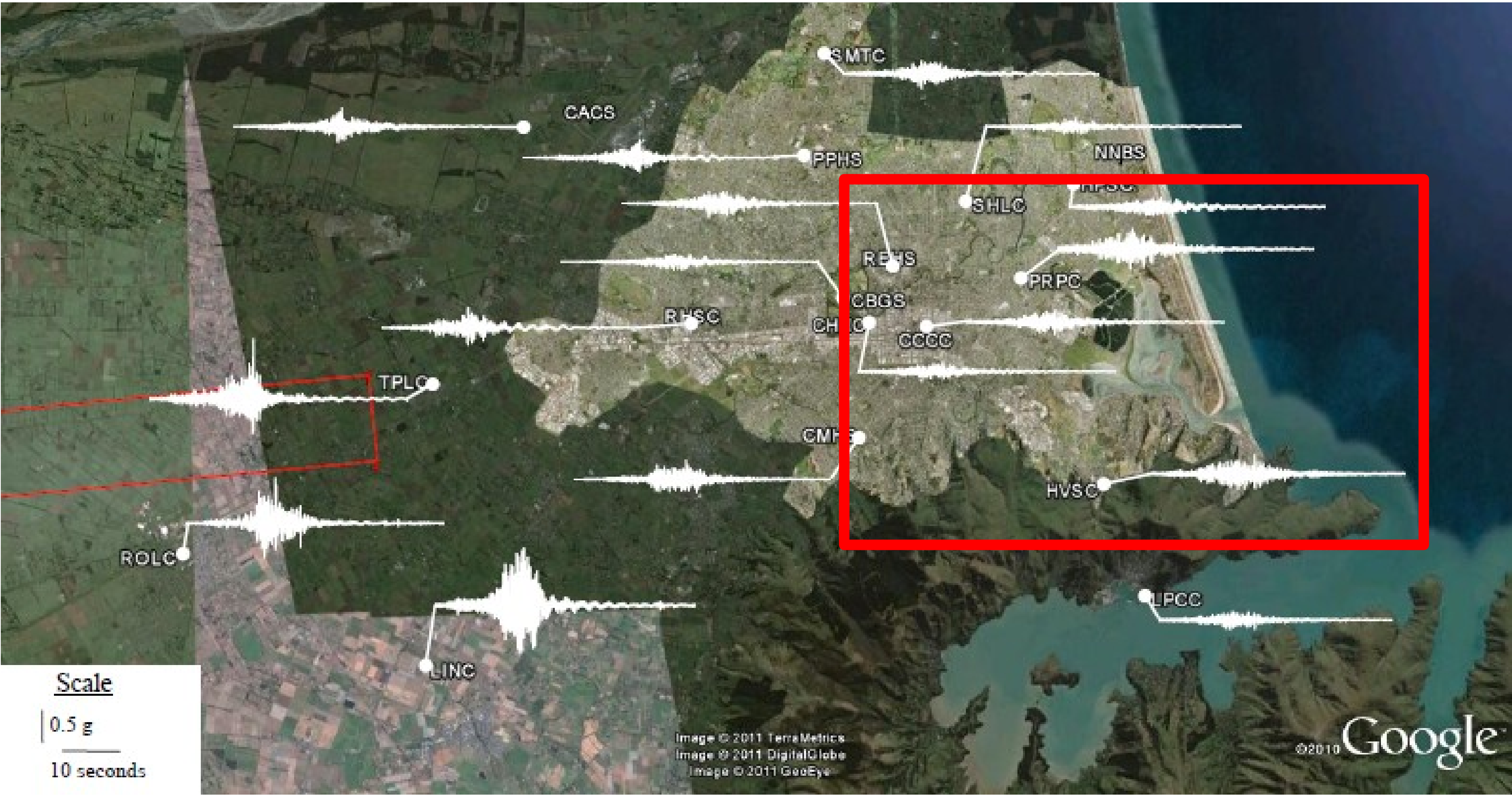
- Separation of soil layers bounds negative acc to [a(t)> -1g], so-called “slap-down” or “trampoline” effect

Ground motion characterization

- Vertical acc's at PRPC and HVSC due to source effect only? – comparison with Sept 4 event

Ground motion characterization

- Site effect on vertical acc's at PRPC and HVSC



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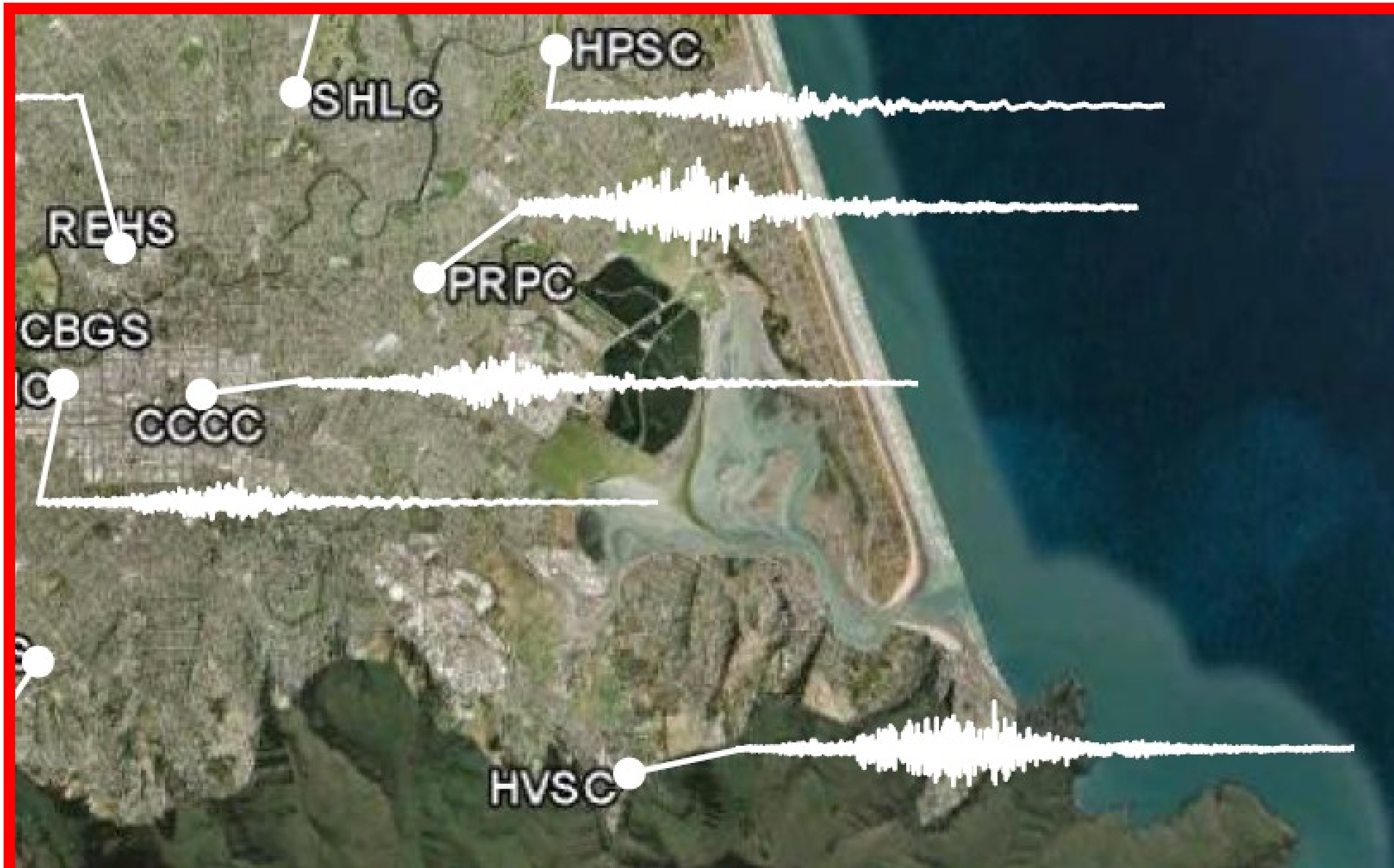
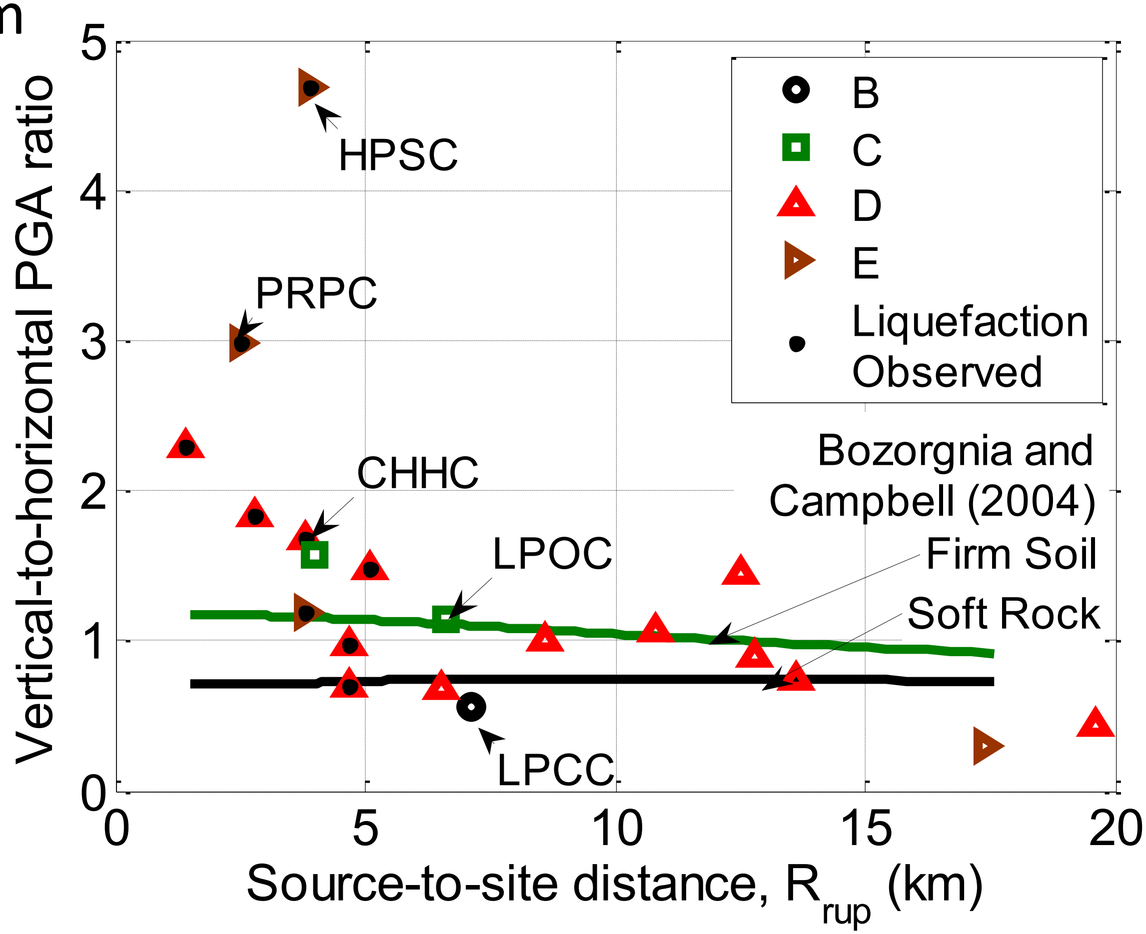


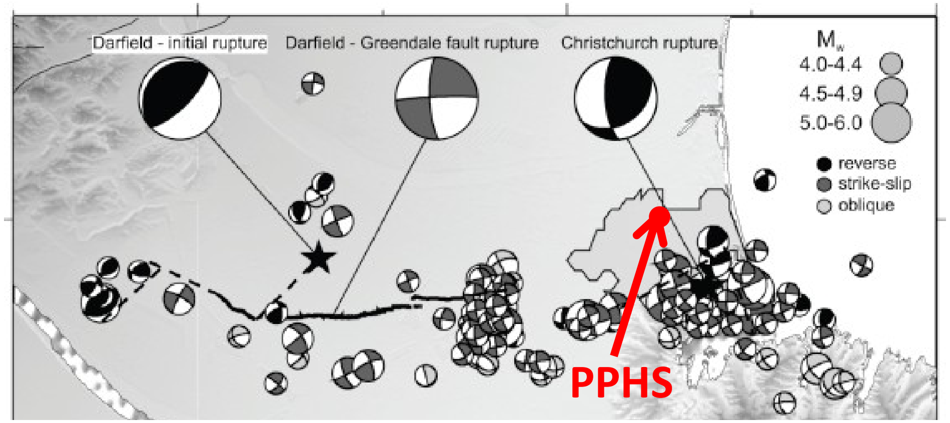
Ground motion characterization

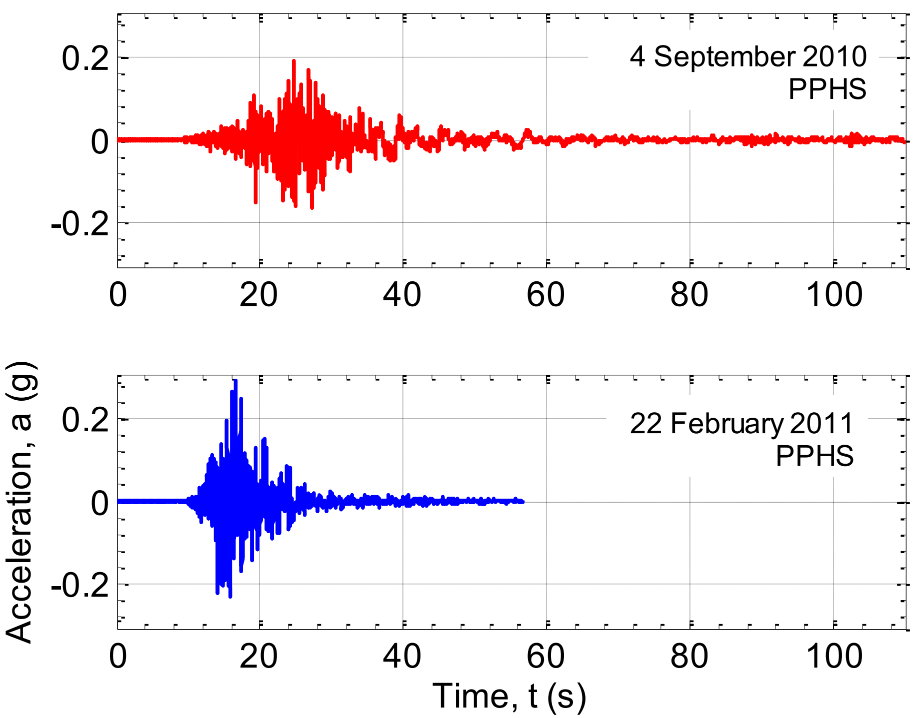
- Vertical-to-horizontal PGA ratio
  - Compare favourably with empirical prediction for R~>5km
  - Liquefaction of near-source sites leads to discrepancy for R<5km

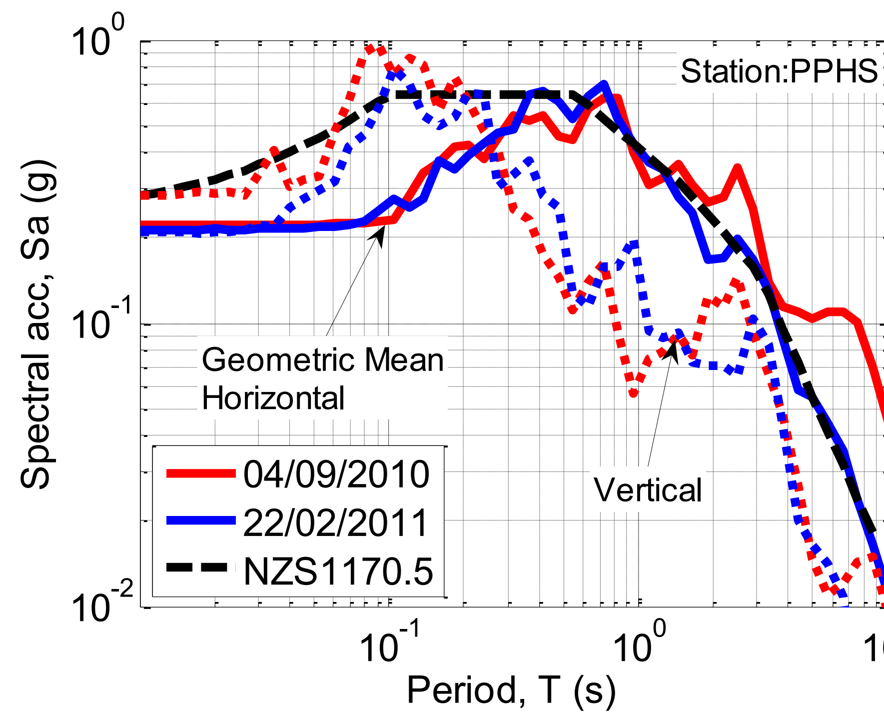


Site response

- Response at Papanui (PPHS) in two events







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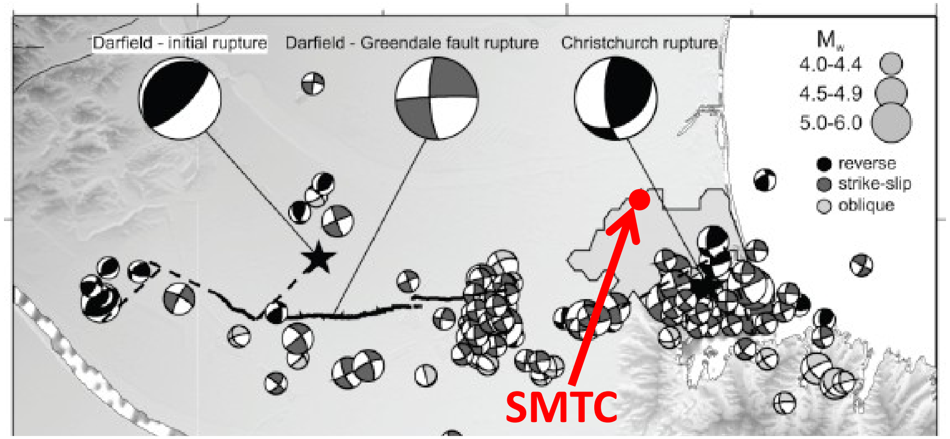
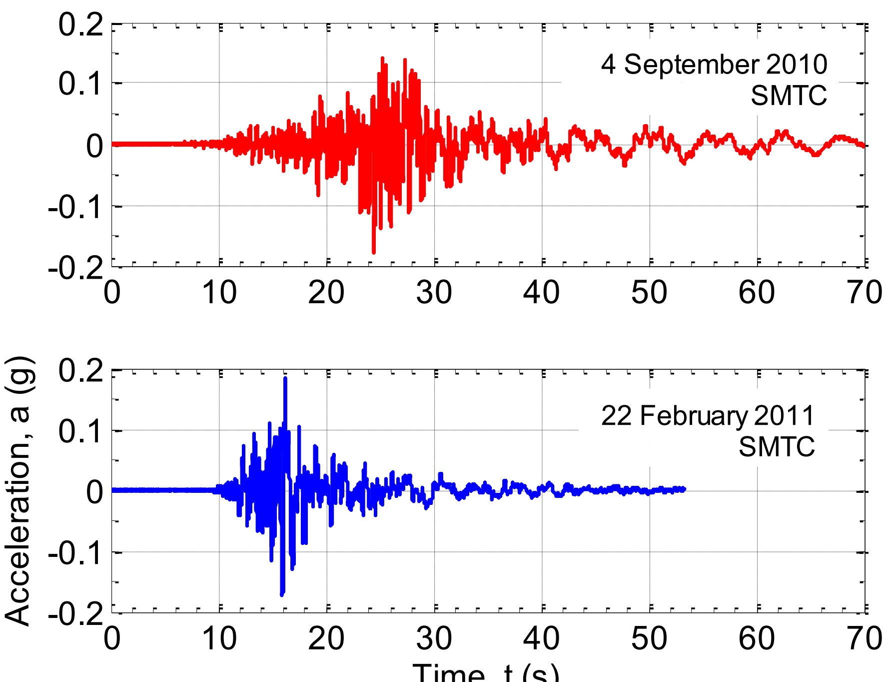
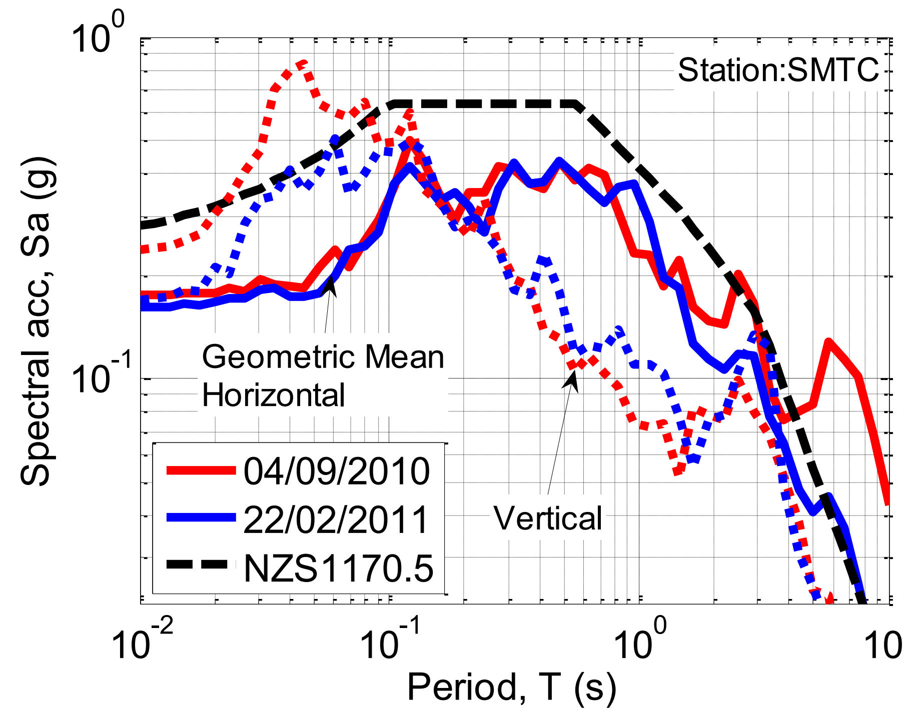
Site response

- Response at Styx Mill (SMTC) in two events







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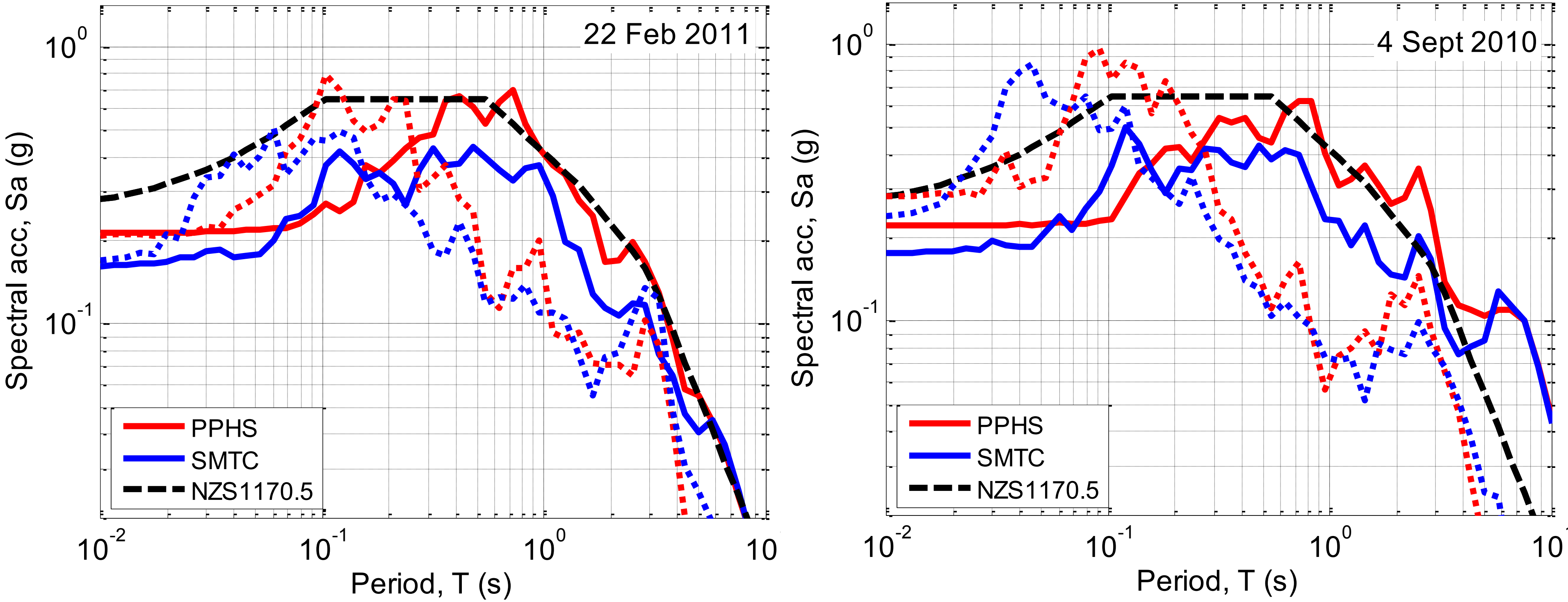
Site response

- Response at PPHS and SMTC in both events



- SMTC has systematically higher site response for T=0.15s
- PPHS has systematically higher PGA and SA(T=0.2-3s)

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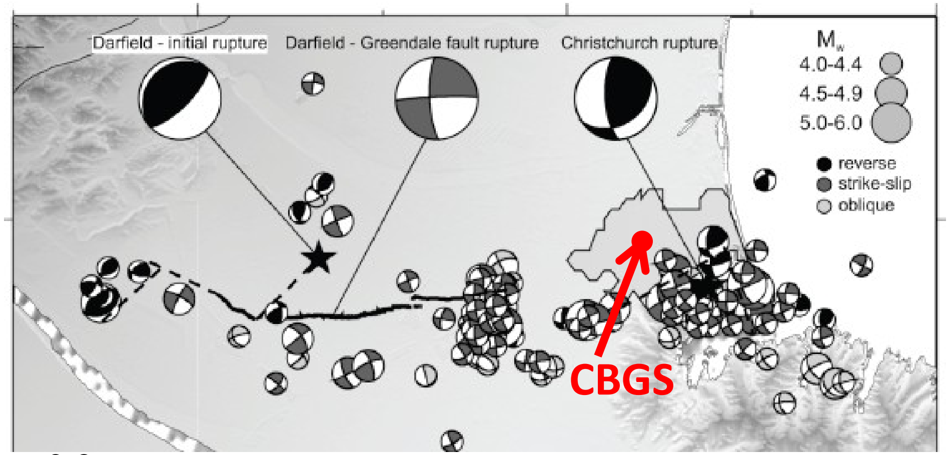
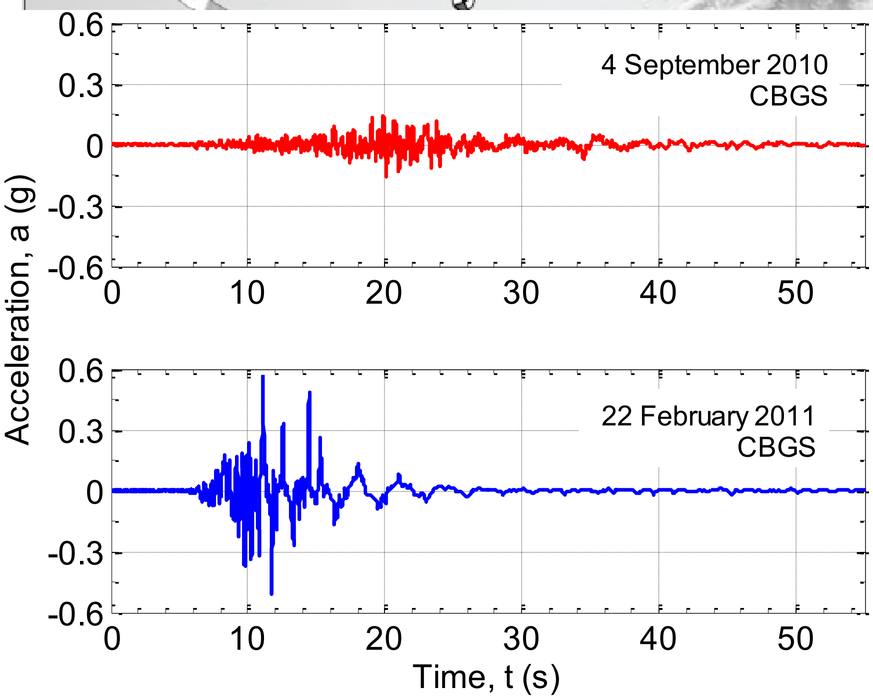
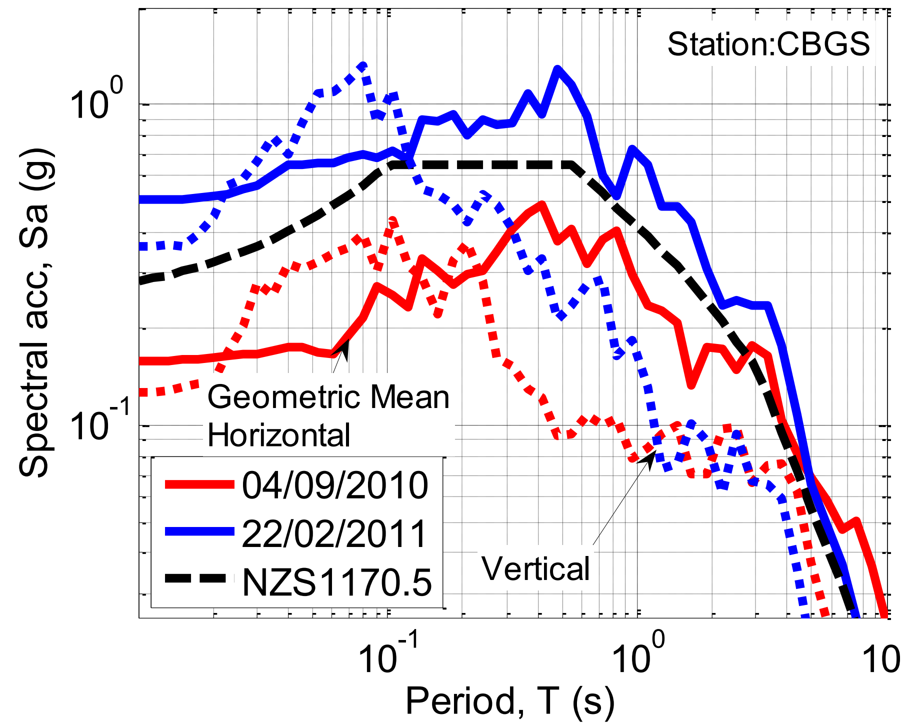
Site response – loose liquefiable soils

- Botanic gardens (CBGS) in two events







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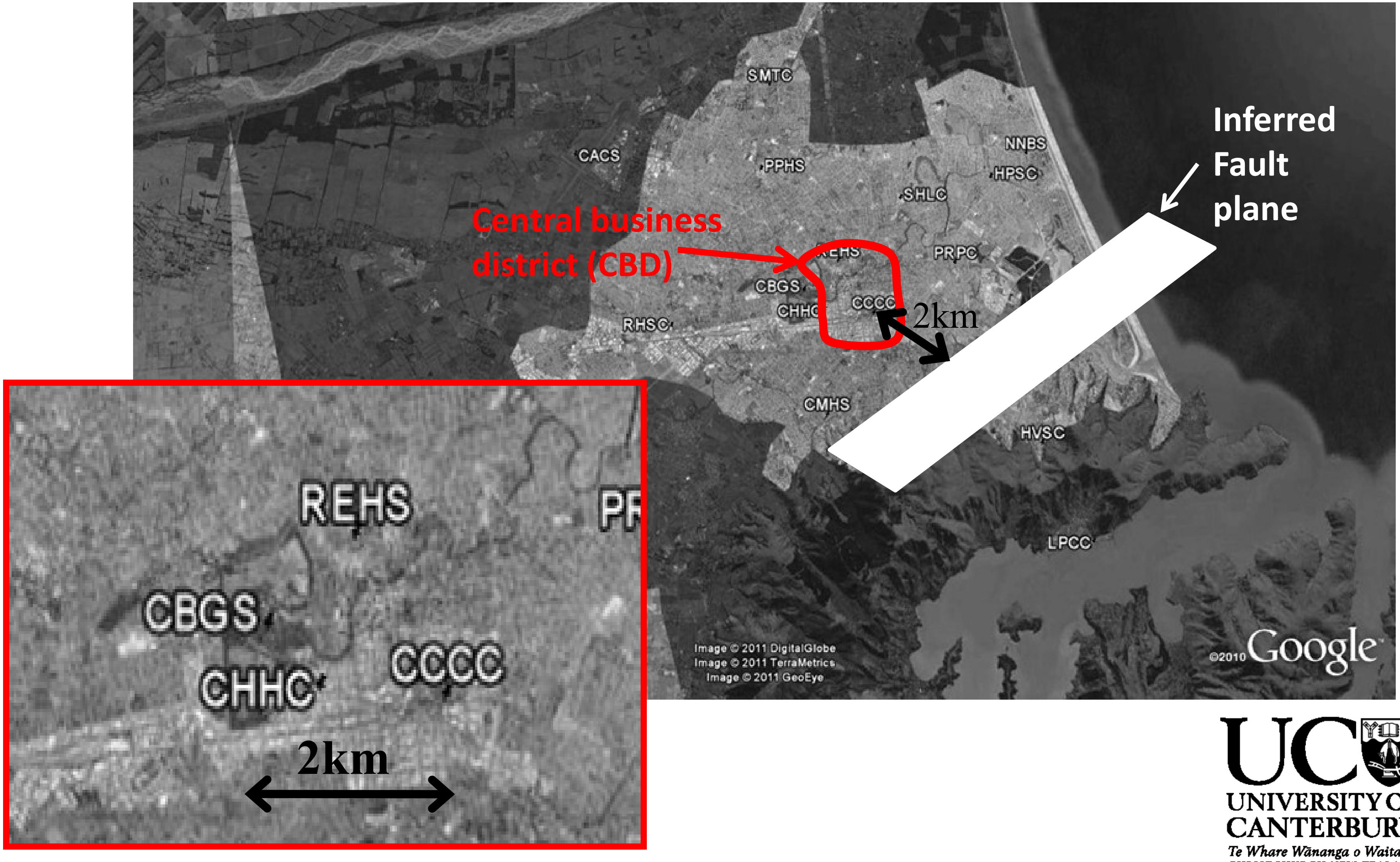
Ground motion characterization

- Seismic demand in Central Business District (CBD)



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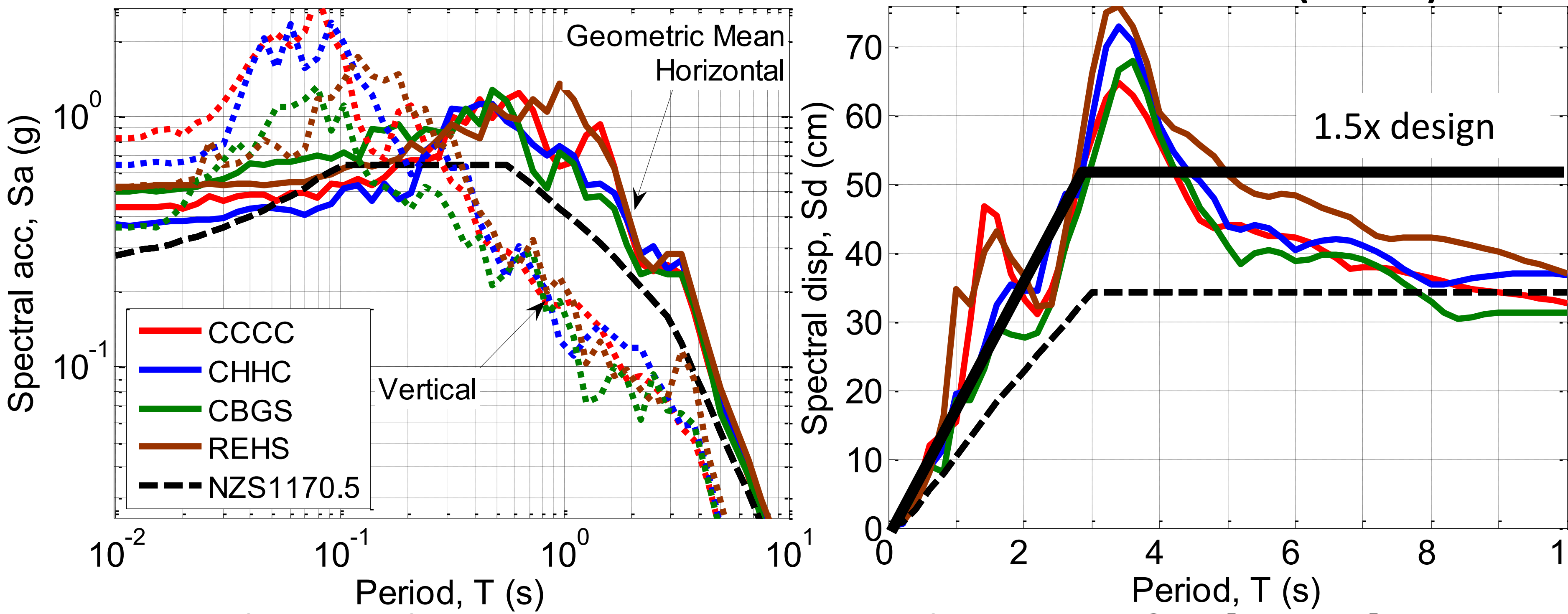
Ground motion characterization

- Seismic demand in Central Business District (CBD)



- Exceeds 1.5x design spectra over a wide range of T=[0.5,5s]
- Strong correlation of long period ground motion intensity
- Effects of local (~30m) soil deposits (spatially variable) pronounced for short periods (PGA_H ranges from 0.4-0.6g)

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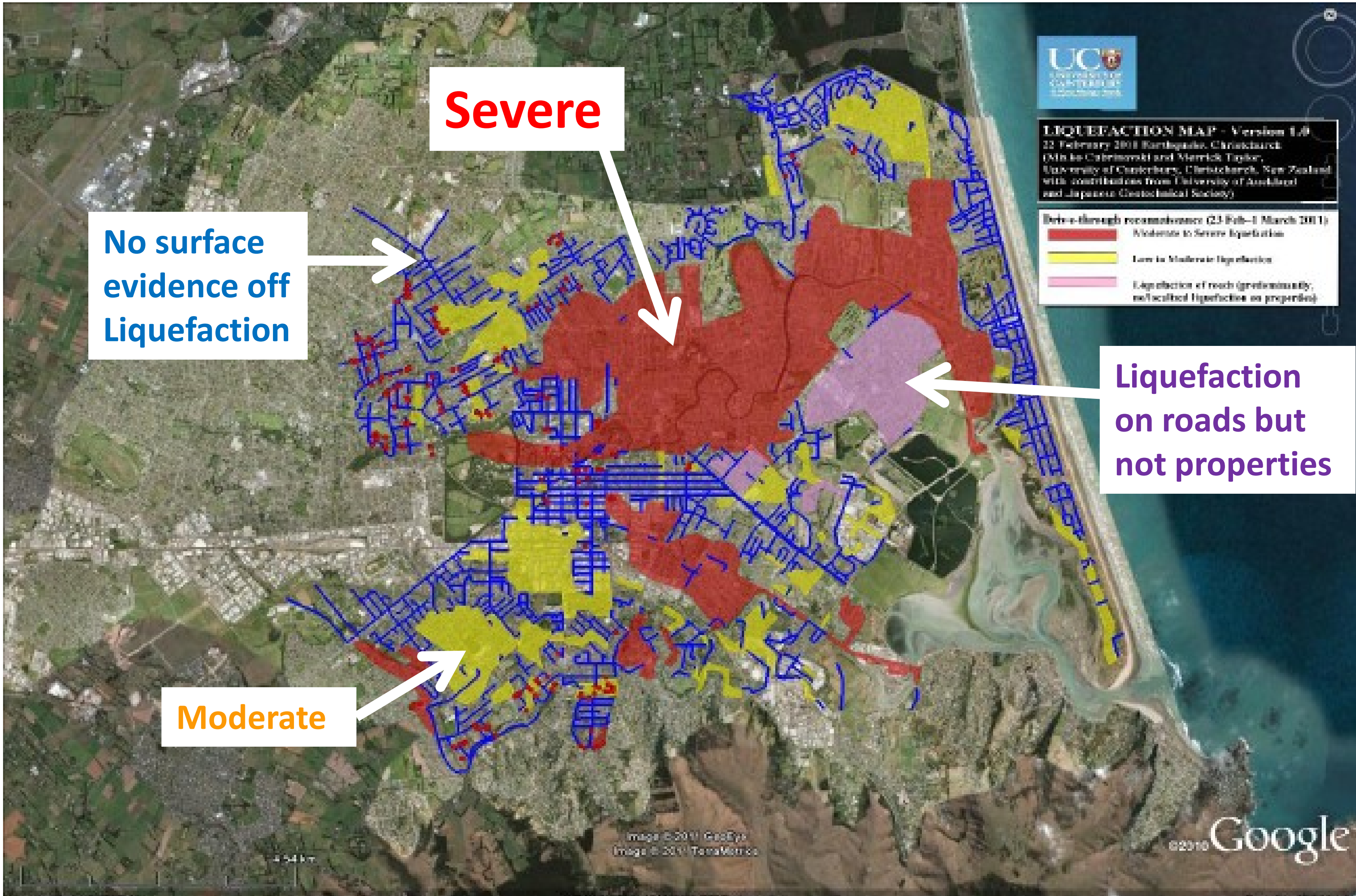
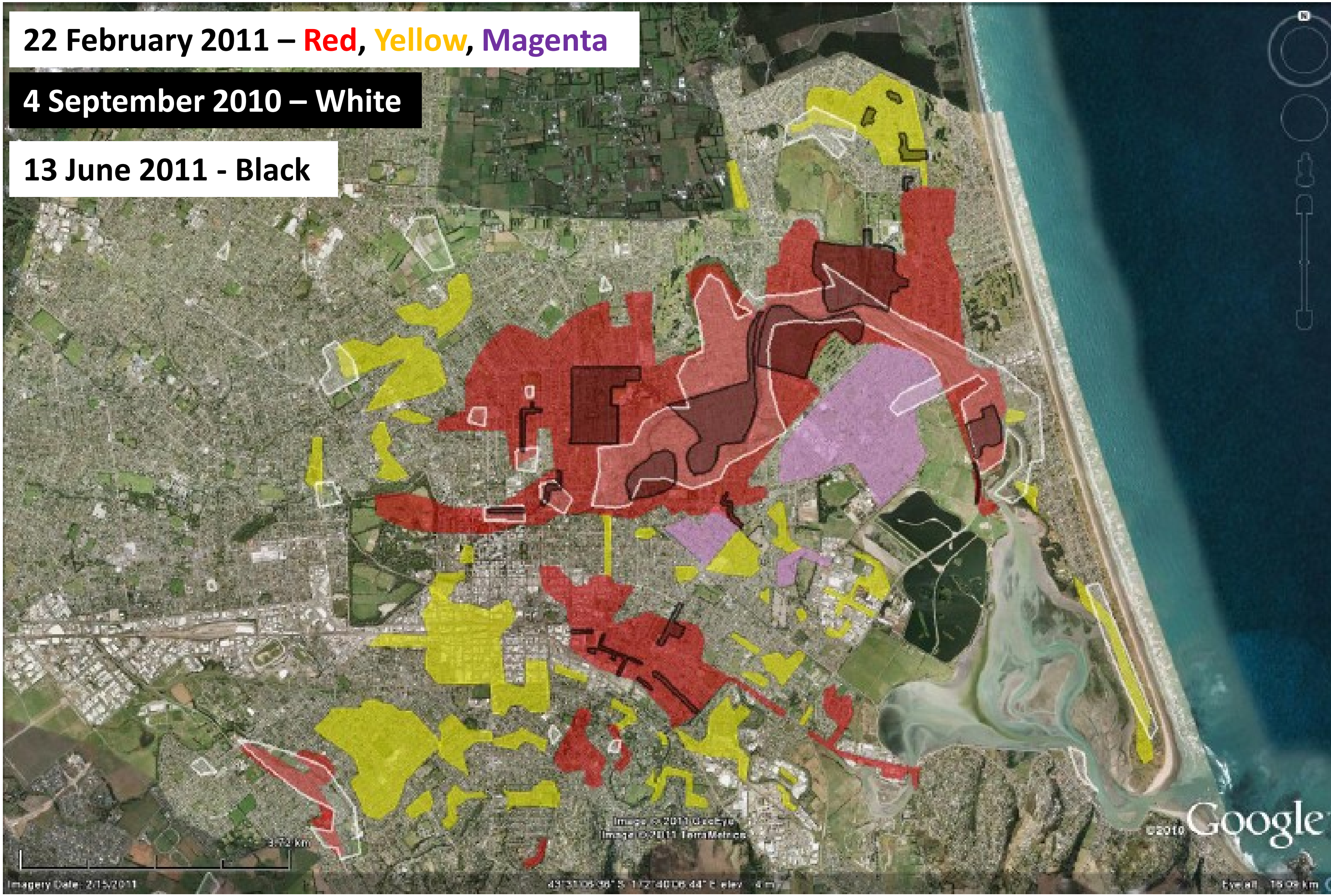
Spatial Extent of Liquefaction



Re-liquefaction in subsequent events



Liquefaction in residential areas

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Liquefaction in residential areas

Contrast with an event such as Kobe 1995, where widespread liquefaction of reclaimed soils in Port area, but minor effects on native soils

Liquefaction in residential areas

<u>Repeated liquefaction</u>
<u>- settlements</u>
40cm – 4 September 2010
50-60cm – 22 Febraury 2011
15-20cm – 13 June 2011

Scale of liquefaction

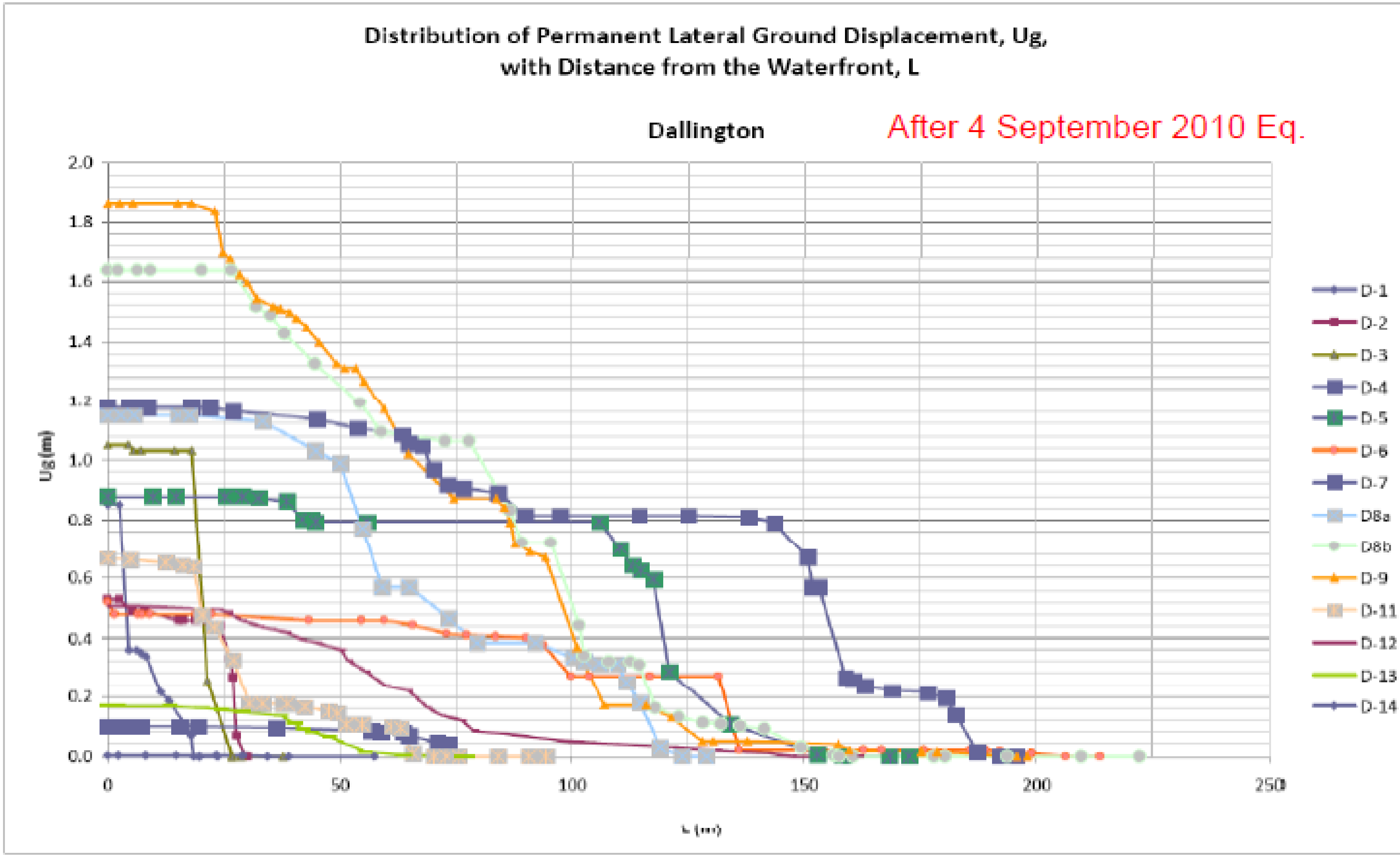
- Approx 500 Million Tonnes of Sand removed from roads and houses

Photo date: 7 March 2011
(~15 days after EQ. It is likely to be 10 times as big now)

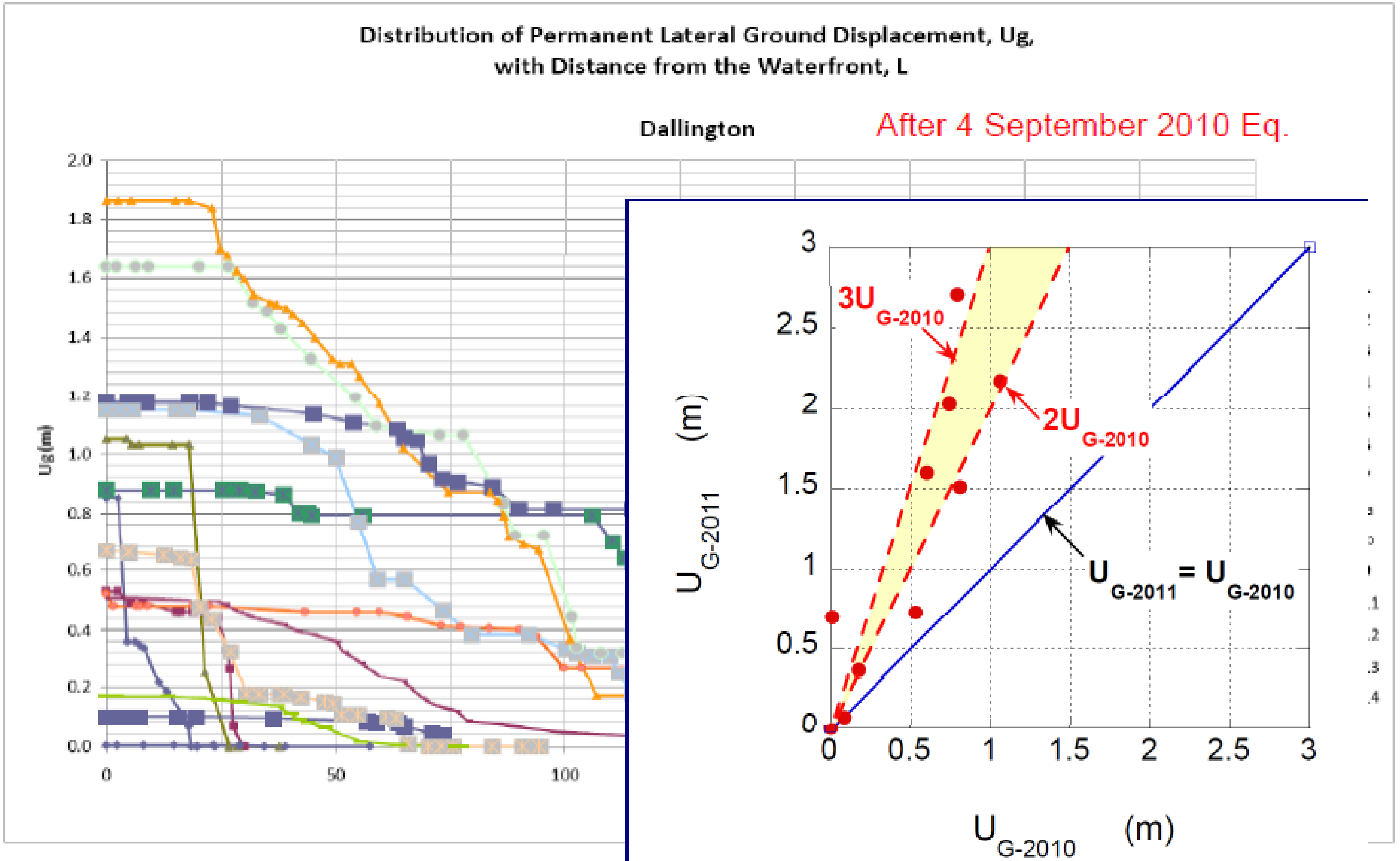
Liquefaction

Lateral Spreading

Distribution of lateral spreading



Distribution of lateral spreading



Lateral spreading block - Kaiapoi

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Lateral spreading – Courtenay Drive

- Severe impacts to residential structures
- Fortunately, ductile light timber construction so no collapses

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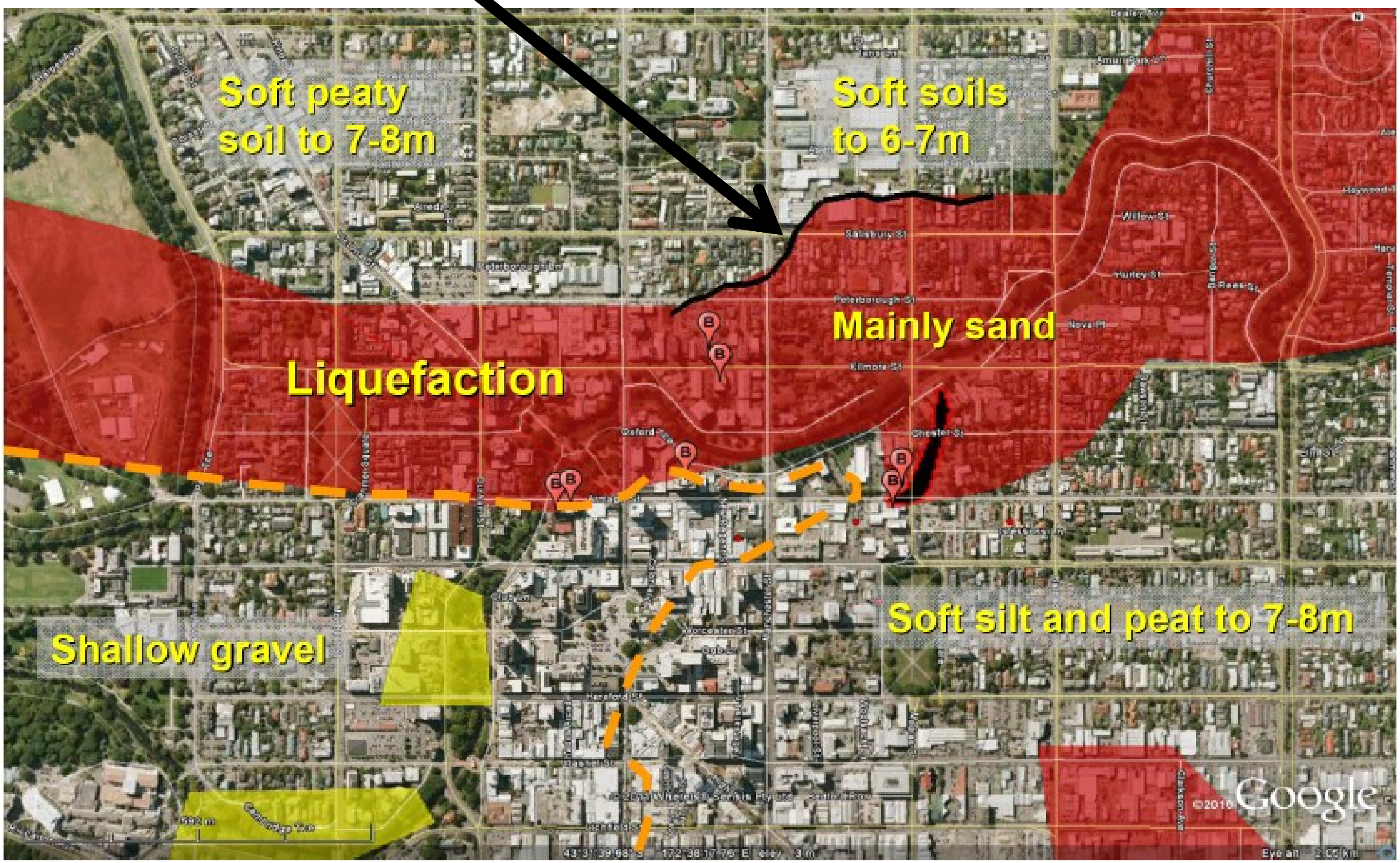
Liquefaction in Central Business District

- Some evidence of clear geomorphologic features



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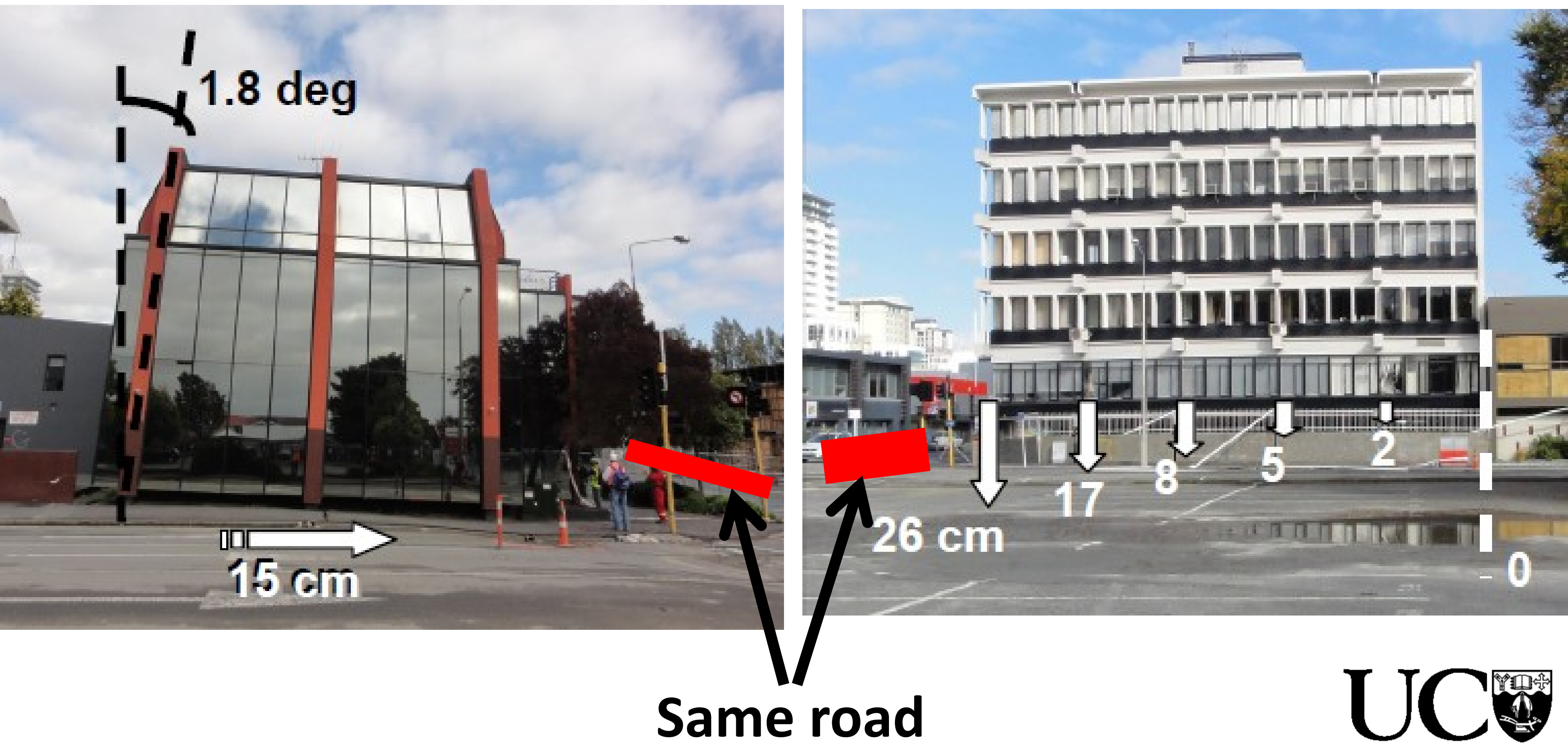
B. Bradley

Liquefaction-induced damage

– Tilting of structures on shallow foundations



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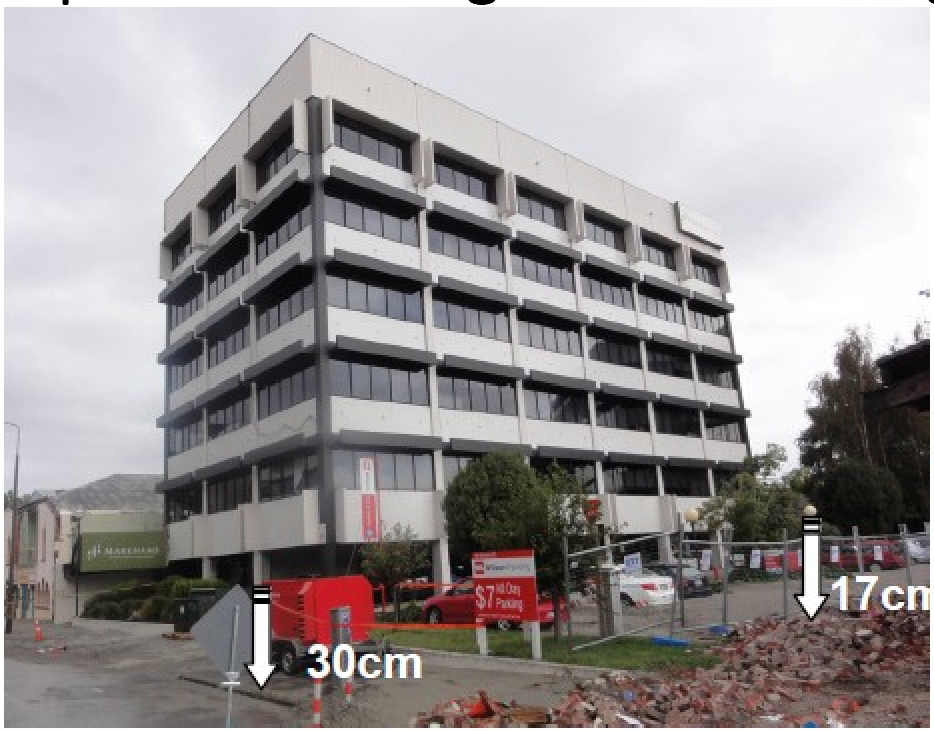
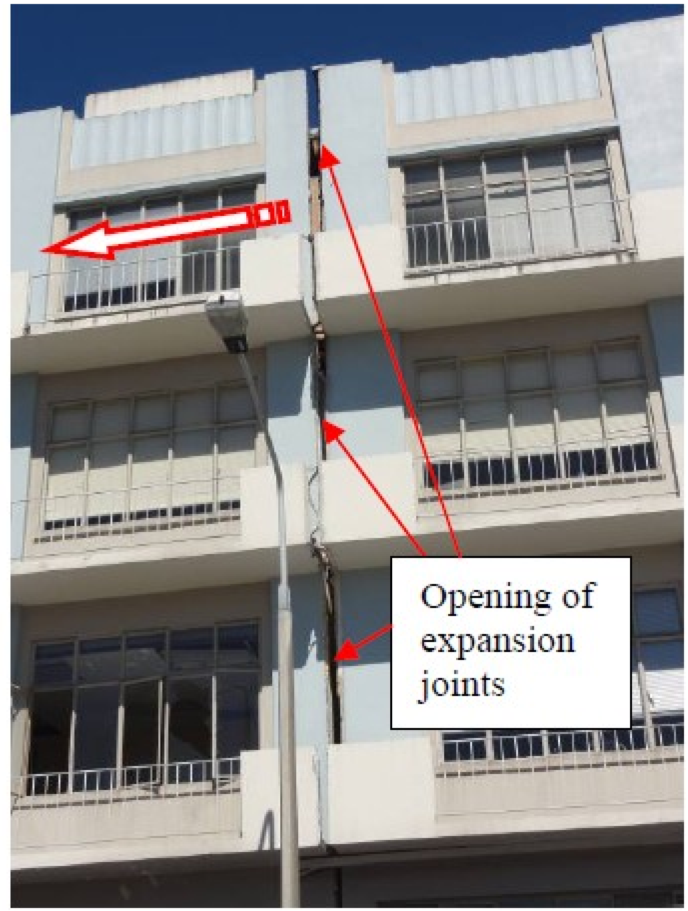
Liquefaction-induced damage

- Settlements of up to 50cm around pile founded structures (after 3 main events), but foundation performance good if founding depth sufficient



Liquefaction-induced damage

- Lateral spreading toward Avon River



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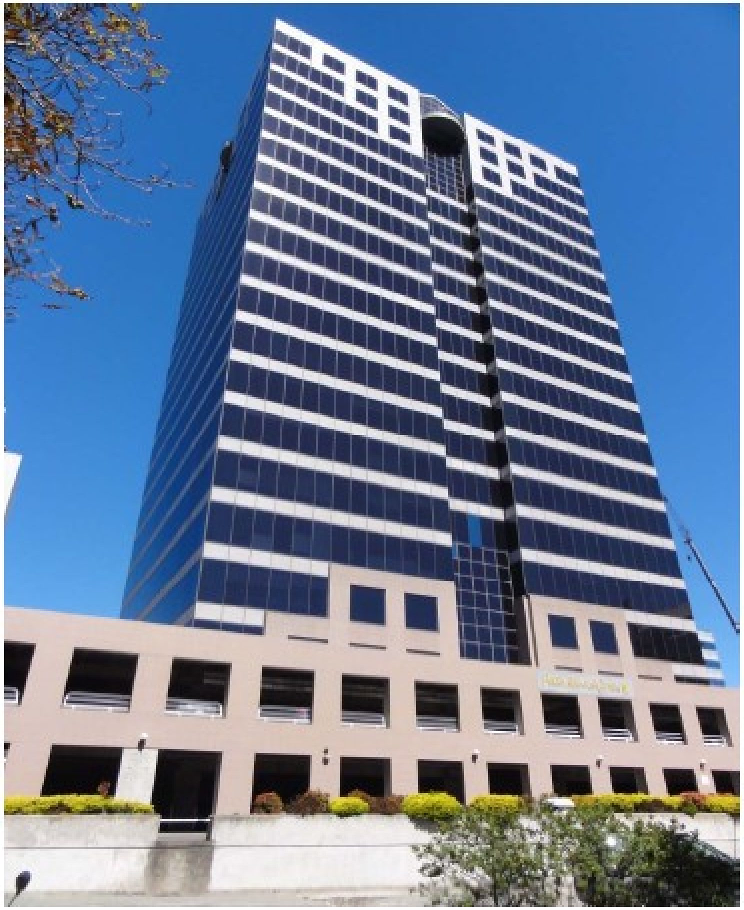
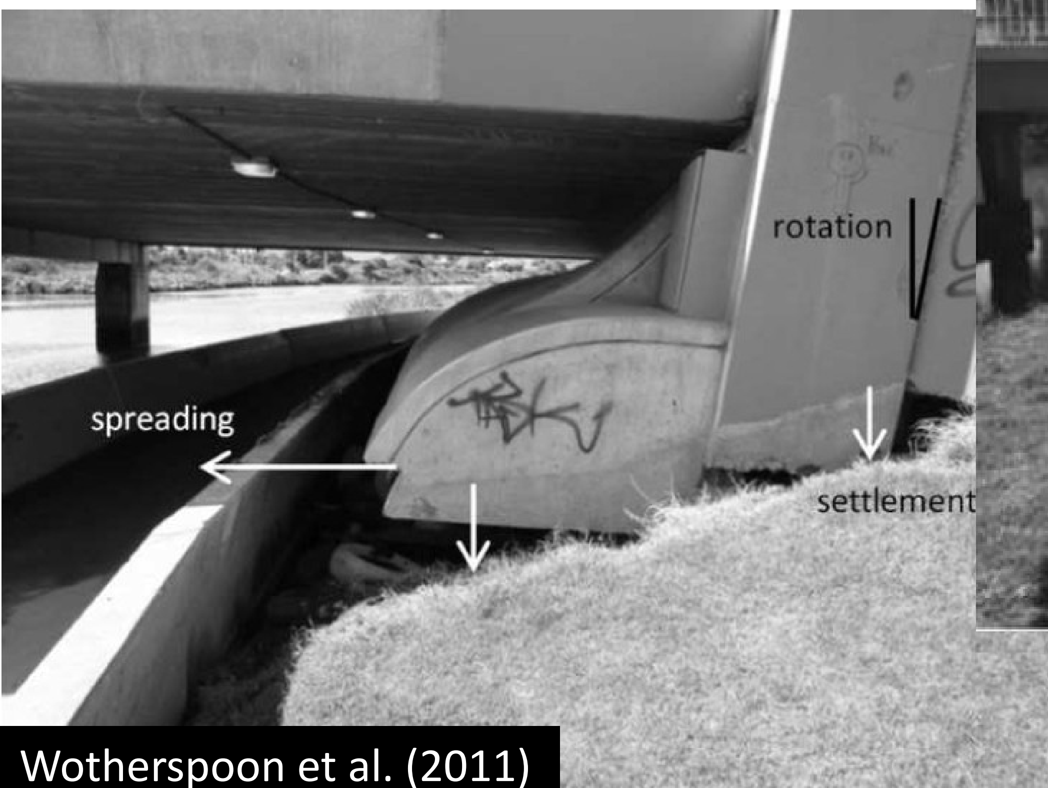
Liquefaction-induced damage

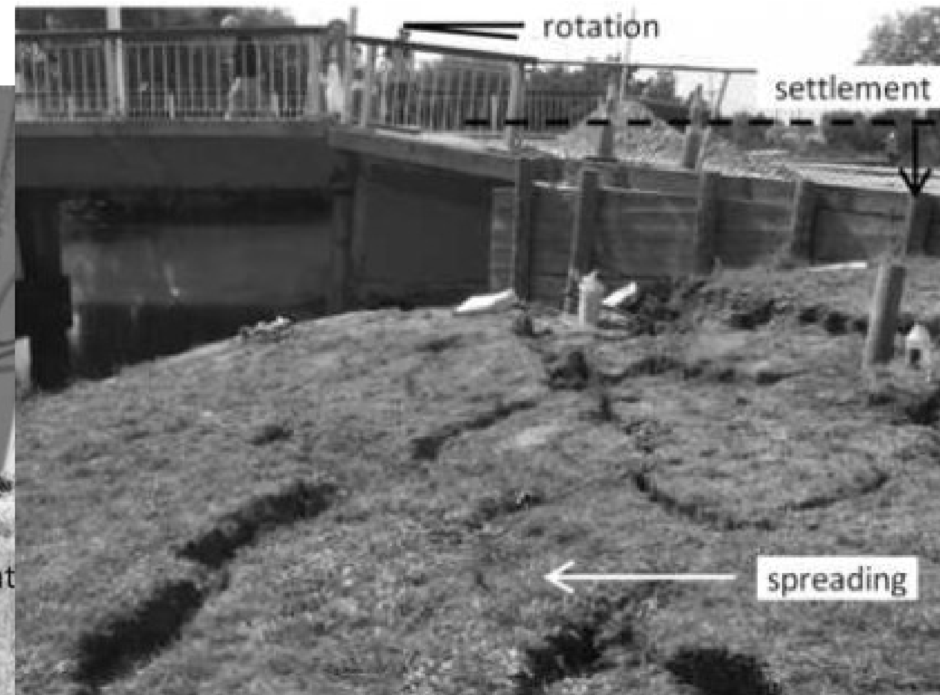


- Traces of liquefaction (spreading in the vicinity)
- Raft foundation
- Ground settlement: ~ 20 cm

Bridge response

- Bridges
  - Primarily liquefaction related damage due to lateral spreading at abutments





Wotherspoon et al. (2011)

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Structural response

- Shaking-induced damage - masonry

Reinforced masonry performed well given intensity of ground shaking in CBD
However, large number of retrofitted facades failed – bolt pullout

Photo courtesy of Weng Y Kam

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Structural response

- Non-ductile RC – 2 collapses (PGC, CTV) – account for majority of 181 causalities

Photo courtesy of Weng Y Kam

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Structural response

- Ductile RC

Photo courtesy of Weng Y Kam

Large single cracking in plastic hinges rather than distributed cracking observed in laboratory testing – may require review of loading protocols

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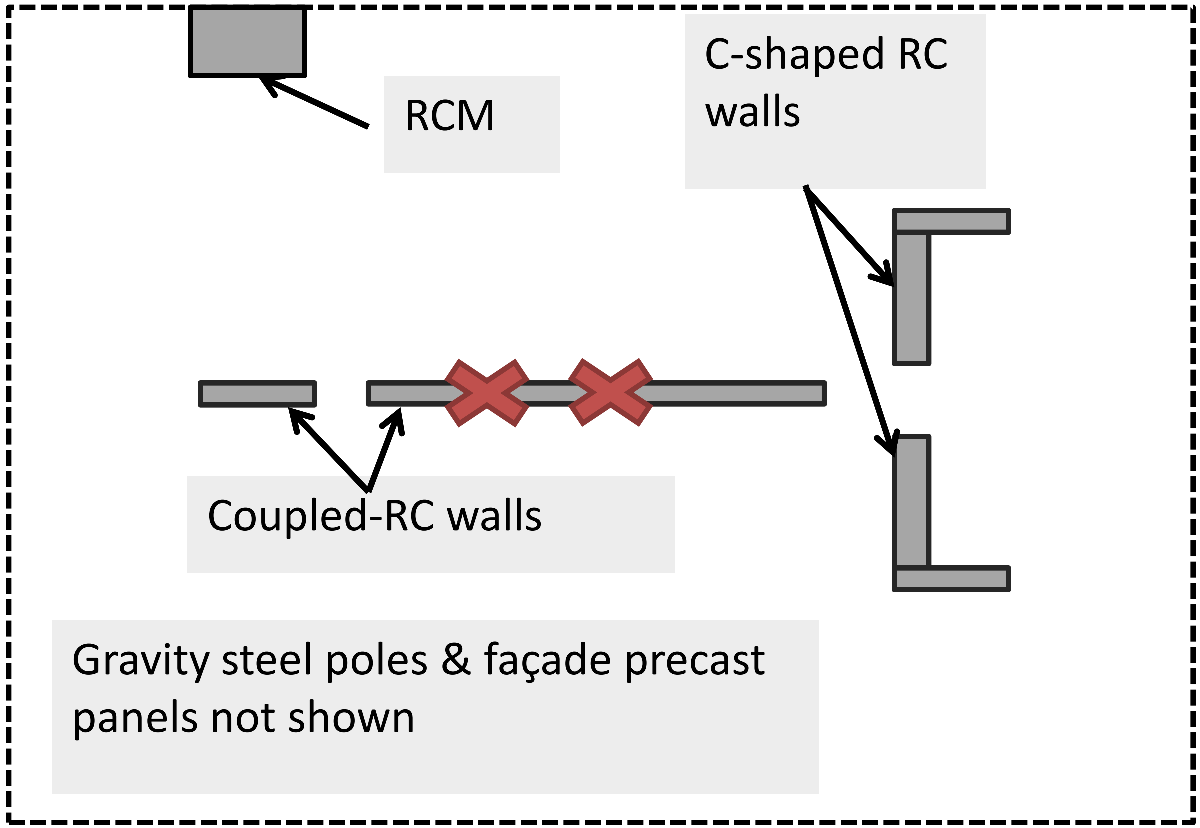
Structural response

- Slender RC walls

Photo courtesy of Weng Y Kam



Structural response

City-wide damage

- A view from the port hills

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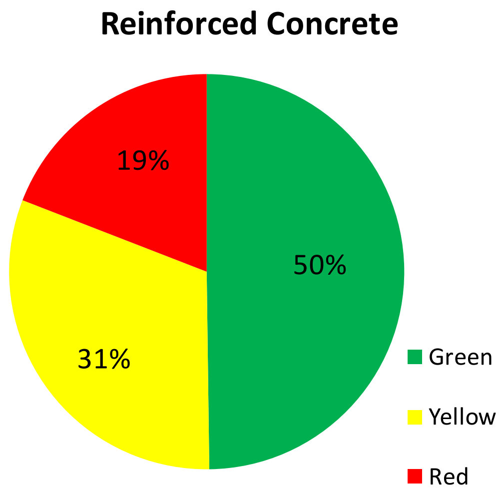
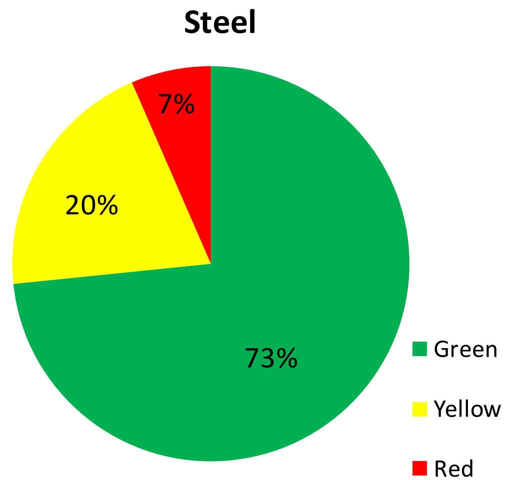
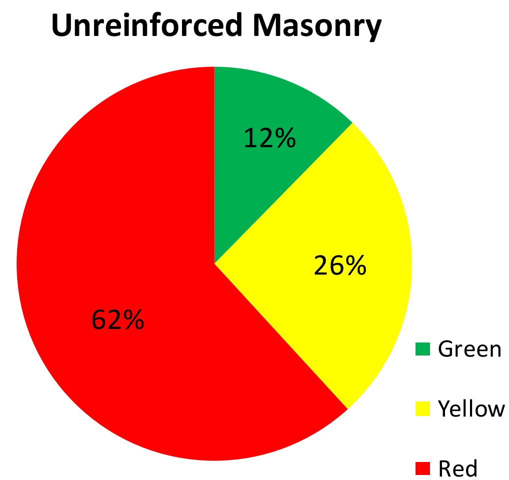
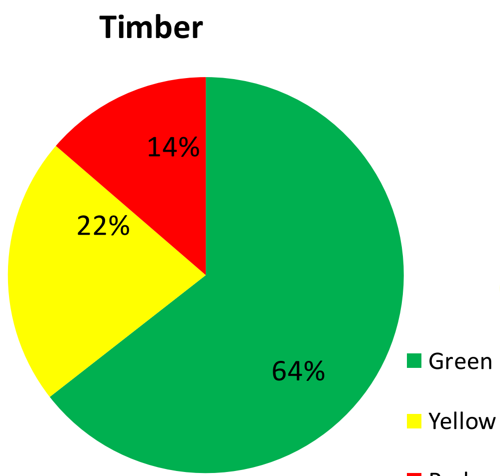
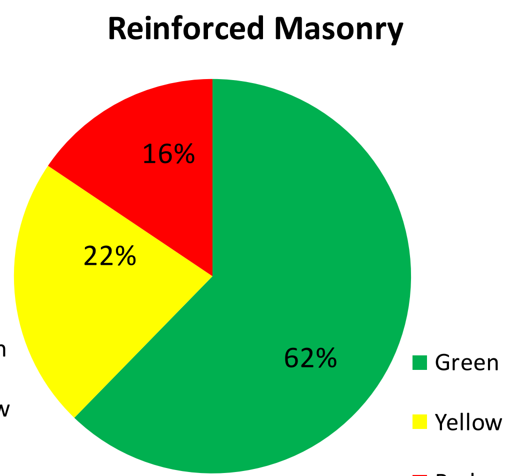
Infrastructure consequences

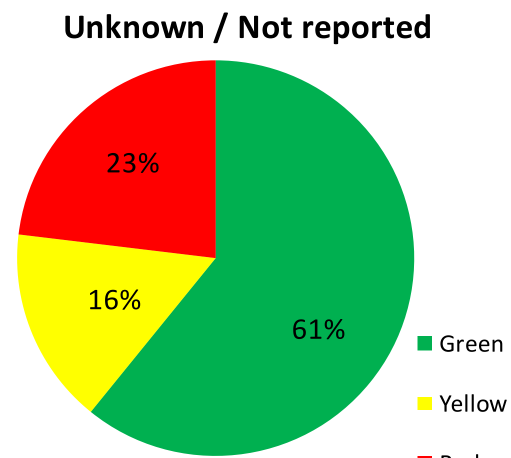












As per 18 Mar 2011 – CCC Data

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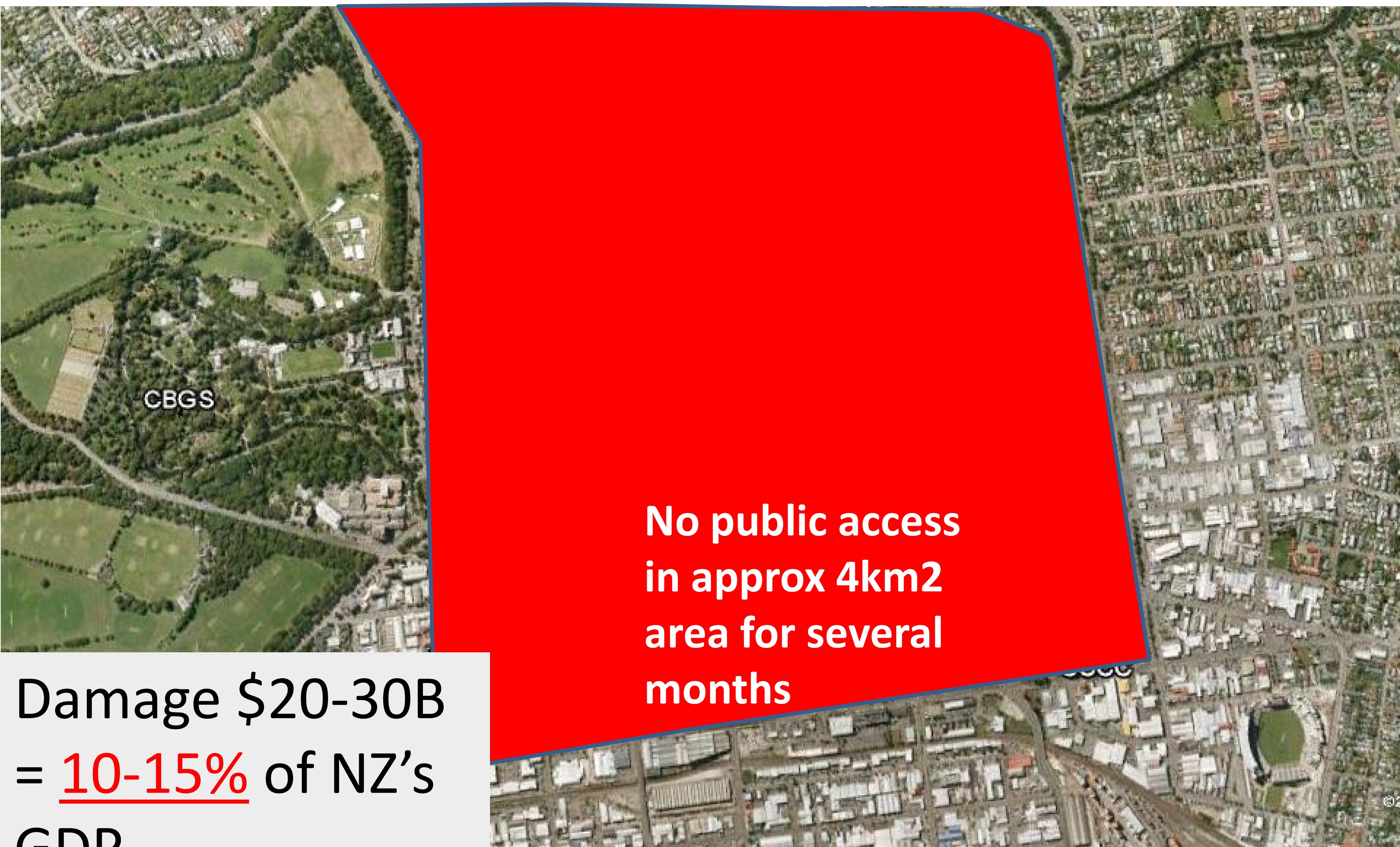
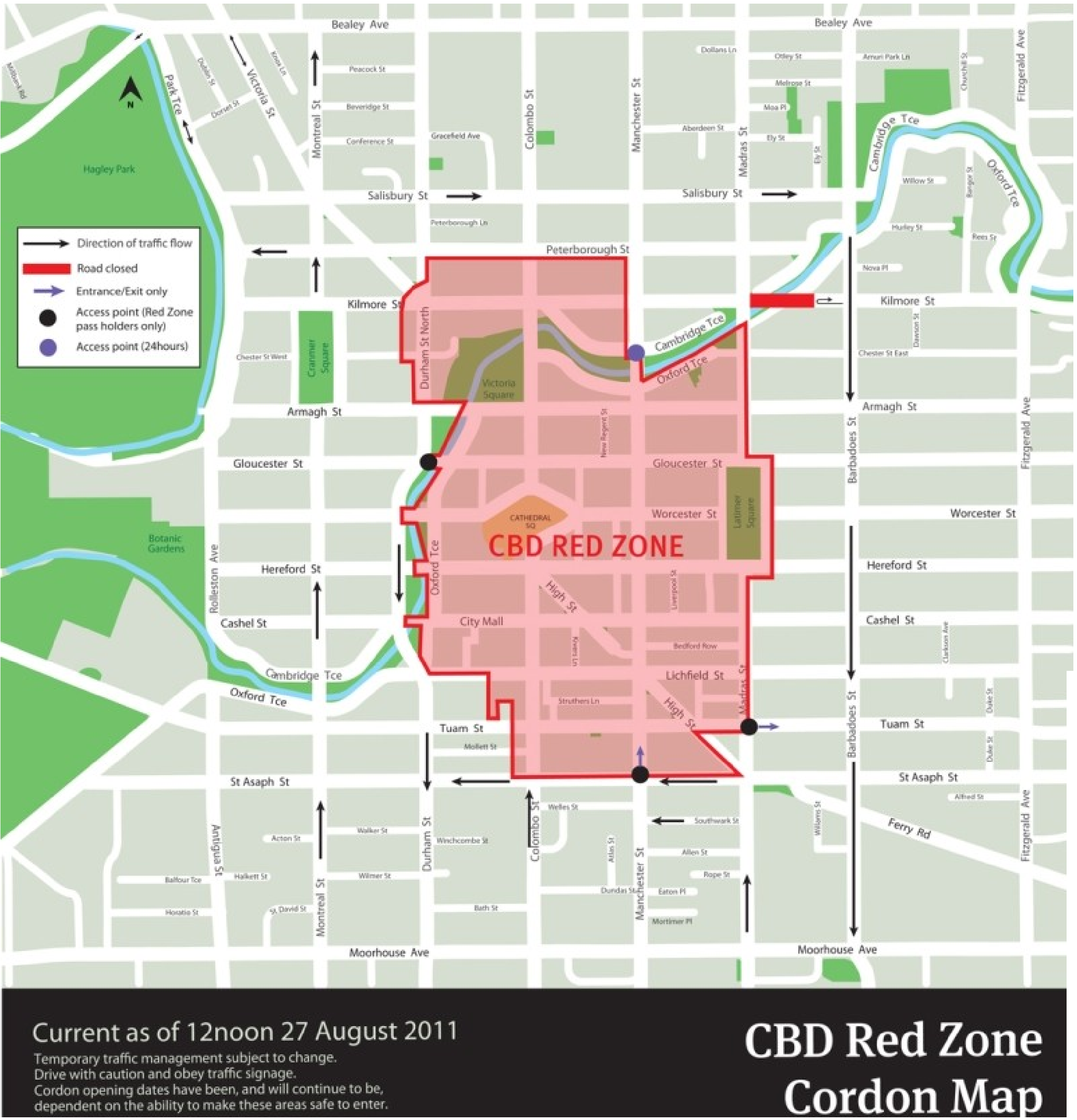
Infrastructure consequences



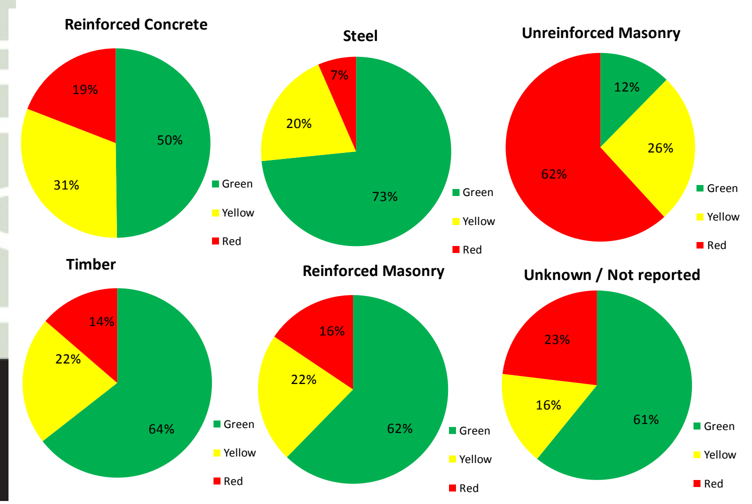
Damage \$20-30B = 10-15% of NZ's GDP

B. Bradley

Infrastructure consequences



- Inner city cordon as of today – (6.5months) - approx 1.1km^2
- Plan to have fully open by April 2012 (>13months)



How can we improve characterization? (1/2)

Fundamental and applied research

- Although specific causal fault(s) were not mapped, the possibility of low slip-rate faults under the Canterbury plains was well recognised (and modelled)
  - Even ‘small’ faulting produces ground motions in the immediate near-source region that are destructive (particularly at high frequencies). Hence, greater attention should be given to faulting possibilities directly below major cities
  - Would explicit modelling of these faults have changed the hazard?
- Observed ground motions were largely consistent with empirical models and numerical simulations, and observed ground motion phenomena are well explained using physical reasoning
  - Importance of near-source directivity; and deep sedimentary basin effects -> improved modelling these phenomena, and consistent inclusion into start-of-practice GMPEs needed, (and are already considered in numerical simulations -> a paradigm shift toward physics-based GM modelling envisaged).
- Pronounced site response in surface ground motions
  - Similar ground motions observed at the same site(s) during different events
  - Significant liquefaction at 9 stations in the CBD and eastern suburbs
  - Clearly, more common use of site-specific response analysis is needed as well as improved site classification in analysis/Codes
  - Opinion: Easiest way to reduce variability in strong motion prediction

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How can we improve characterization? (2/2)

Seismic mitigation / design guidelines

- By definition "rare" events will not be adequately represented by the 1/475yr seismic hazard (conventionally used in seismic codes).
  - Consideration must be given to both different exceedance probabilities (for PSHA), and also scenario events (i.e. from DSHA) in assessing seismic performance
  - This should aid in communication of seismic performance expectation of structures
- The state of the Christchurch CBD illustrates that, in metropolitan areas, the *performance* of a single structure is also dependent on the average seismic resilience of all other structures in its vicinity
  - This will be controlled by the minimum allowable performance for pre-code structures, and how well this is enforced by local authorities – system problem
- Improved classification of the potential for ground failure is needed, based on more than insitu elastic properties, and appropriate methods for assessment defined

Thank you for your attention

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